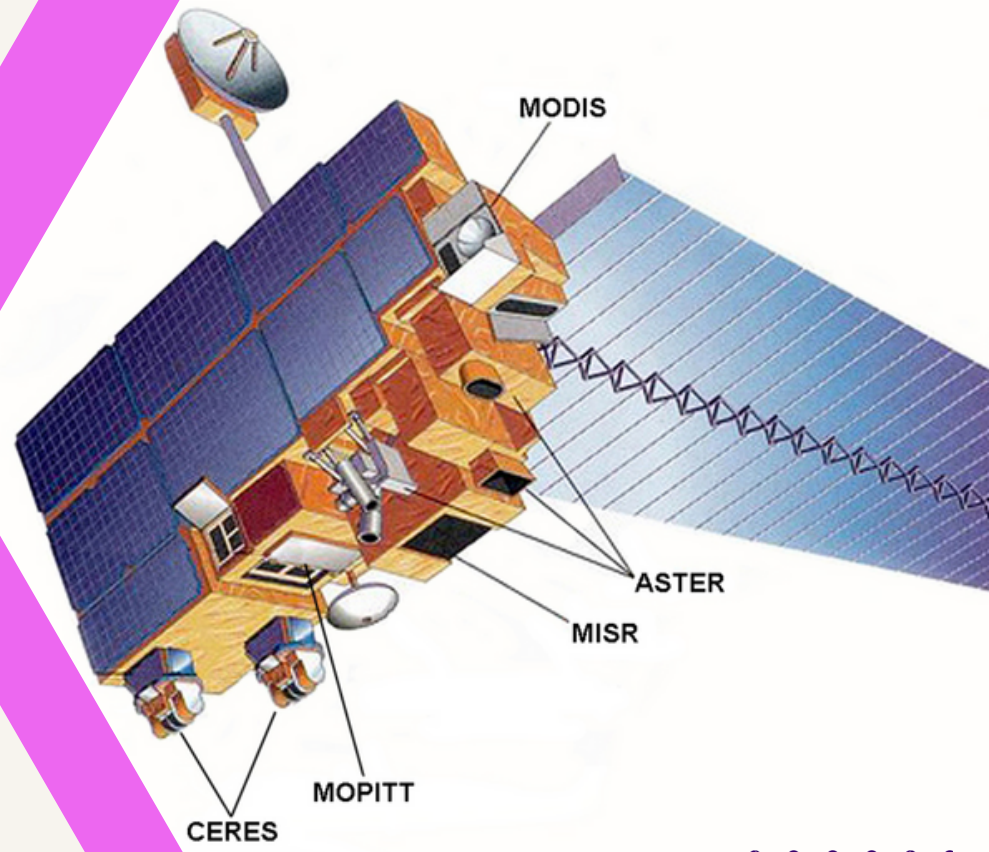
Moderators:
Nyssa Rayne, GSFC
Jennifer Brennan, GSFC

TERRA'S LOWER ORBIT

VIRTUAL COMMUNITY FORUM



DECEMBER 8, 2022
12:30 PM – 3:30 PM ET

terra.nasa.gov

NASA

GODDARD EARTH SCIENCES

Forum Agenda

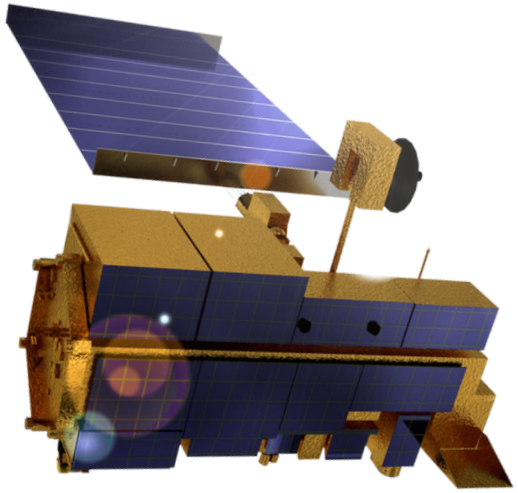
INTRODUCTION
Kurt Thome, Terra Project Scientist

OVERVIEW OF TERRA ORBIT LOWERING MANEUVERS
Jason Hendrickson, Terra Flight Systems Manager

DATA IMPACTS BY INSTRUMENT
- **MOPITT** - Helen Worden, *U.S. Principal Investigator*
- **MODIS** - Miguel Román, *Science Team Leader*
- **MISR** - David Diner, *Principal Investigator*
- **CERES** - Norman Loeb, *Principal Investigator*
- **ASTER** - Michael Abrams, *U.S. Science Team Leader*

PHASE F: OVERVIEW AND UPDATES
Kurt Thome, Terra Project Scientist

QUESTION & ANSWERS // COMMUNITY DISCUSSION



PURPOSE & GOALS

The purpose of this community forum is to **inform the scientific community** about the **what** and **why** of **Terra's orbit lowering** that occurred in **October 2022.**

Topics Covered:
- History of Terra's orbit maintenance
- Purpose of lowering Terra's orbit
- Description of lowering maneuvers
- Results from October 2022 lowering
- Discussion of instrument data impacts
- What's next for Terra?

Terra's Lower Orbit Community Forum Introduction

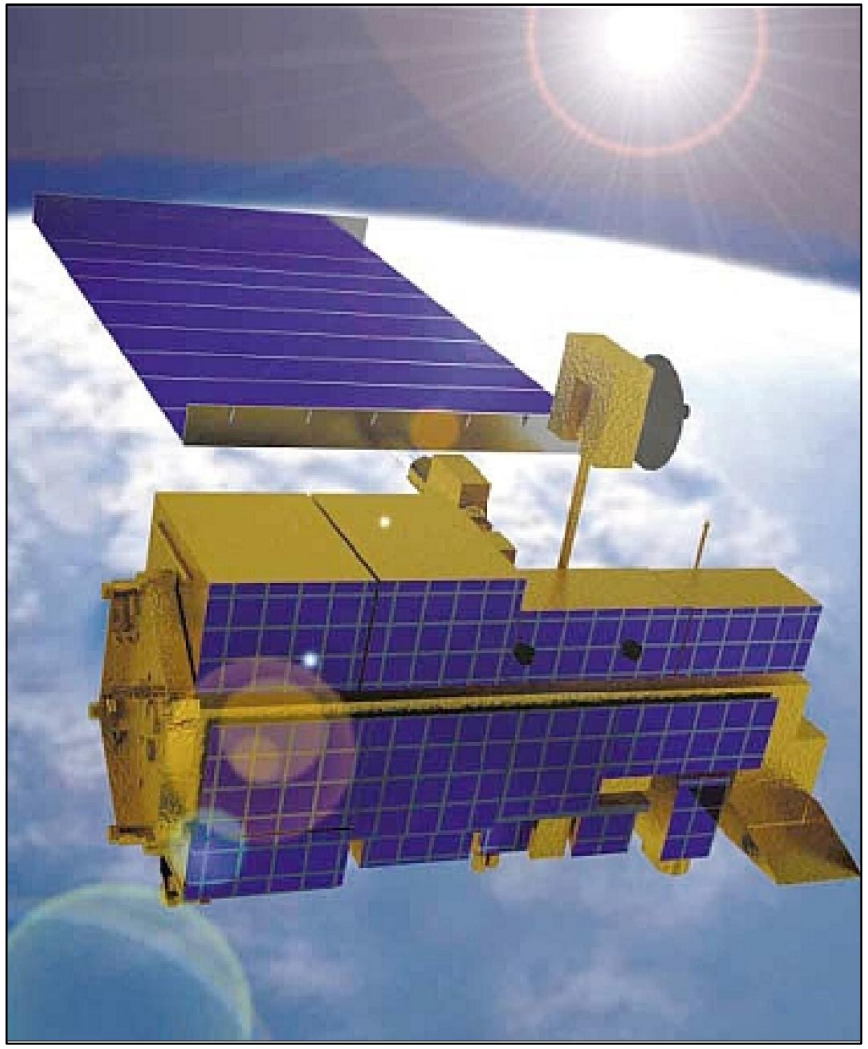
Kurt Thome

NASA/GSFC

Purpose of Terra's Lower Orbit Community Forum

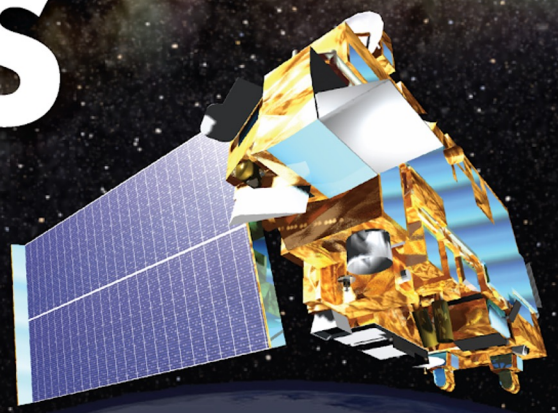
To provide information related to Terra's recent platform maneuvers to lower our orbit

- Terra background
  - Overview of Terra
  - Reminder of Terra's past orbit maneuvers
- Constellation exit maneuver description
- Instrument summaries
  - MOPITT
  - MODIS
  - MISR
  - CERES
  - ASTER
- What to expect next



TERRA

22 YEARS



5 INSTRUMENTS
ASTER • CERES • MISR
MODIS • MOPITT

OVER 100,000 ORBITS

20,000 PUBLICATIONS
350,000 CITATIONS

4.6 MILLION USERS

83 DATA PRODUCTS

Terra summary

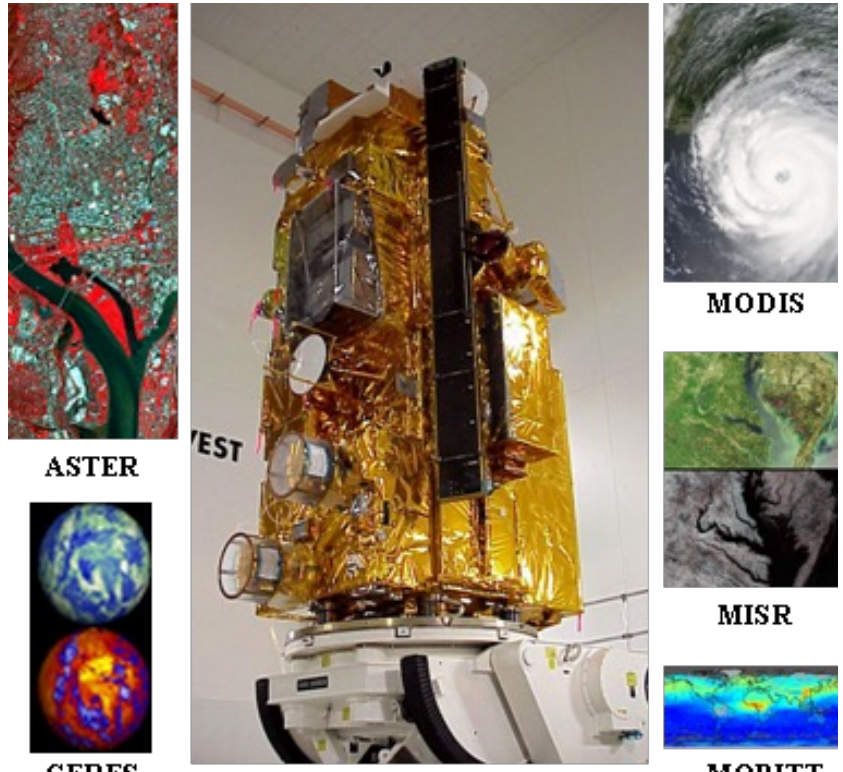
- (GSFC)

Project Scientist (PS)	**Kurt Thome**
Deputy PS	**Si-Chee Tsay**
Deputy PS for Data	**Robert Wolfe**
ESMO Project Manager	**Wynn Watson**

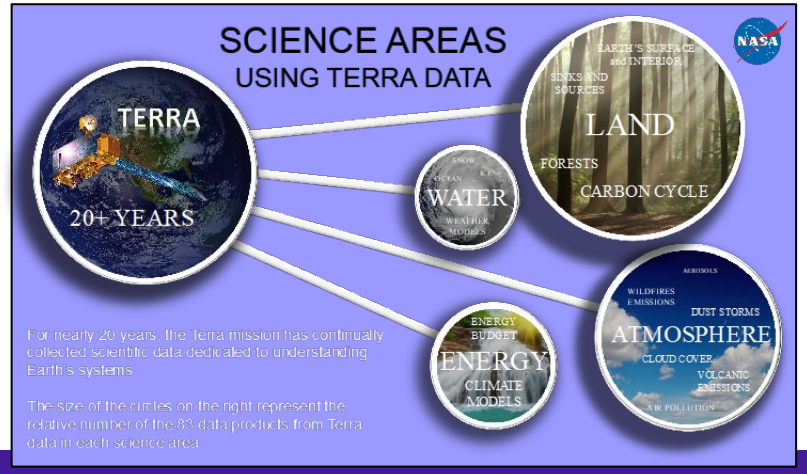
- Instrument PIs & Team Leaders (T.L.)

ASTER	Japan TL US TL	**Yasushi Yamaguchi** **Michael Abrams (JPL)**
CERES	PI	**Norman Loeb (LaRC)**
MISR	PI	**David Diner (JPL)**
MODIS	TL	**Michael King (UC/LASP)**
MOPITT	Canada PI US PI	**James Drummond (Dalhousie Univ.)** **Helen Worden (NCAR)**

- Launch Date: December 18, 1999
- 705-km orbit
- 98.88 minute period
- 98.3 degree inclination
- 16 day repeat (233 orbits)
- 10:30 am crossing time descending orbit (originally 10:45 am)
- Design Life : 6 years



- ASTER
  - Hi-resolution, multi-spectral images from 15 m to 90 m resolution, plus stereo
- CERES
  - Measures Earth's shortwave, longwave, and net radiant energy budget
- MISR
  - Global multiangle images of aerosol, cloud, and surface characteristics
- MODIS
  - 1-2 day global coverage in 36 wavelengths from 250 m to 1 km resolution
- MOPITT
  - Global measures of CO

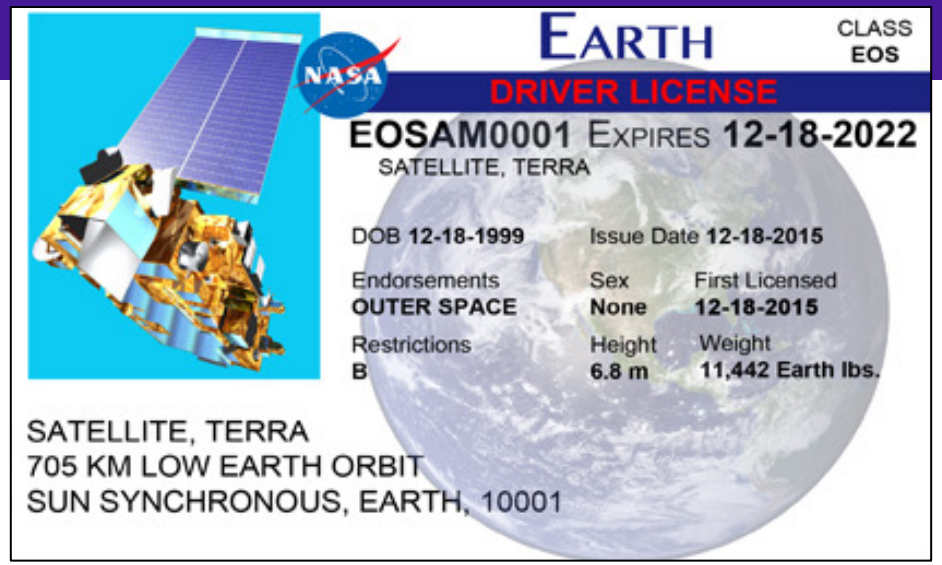


The primary purpose of Terra is to enable the science community to address fundamental questions on causes and pace of global environmental change

The 2020 SR proposal objective was to capitalize on Terra's unique capabilities reflected in continued production of its core data products

Terra Highlights

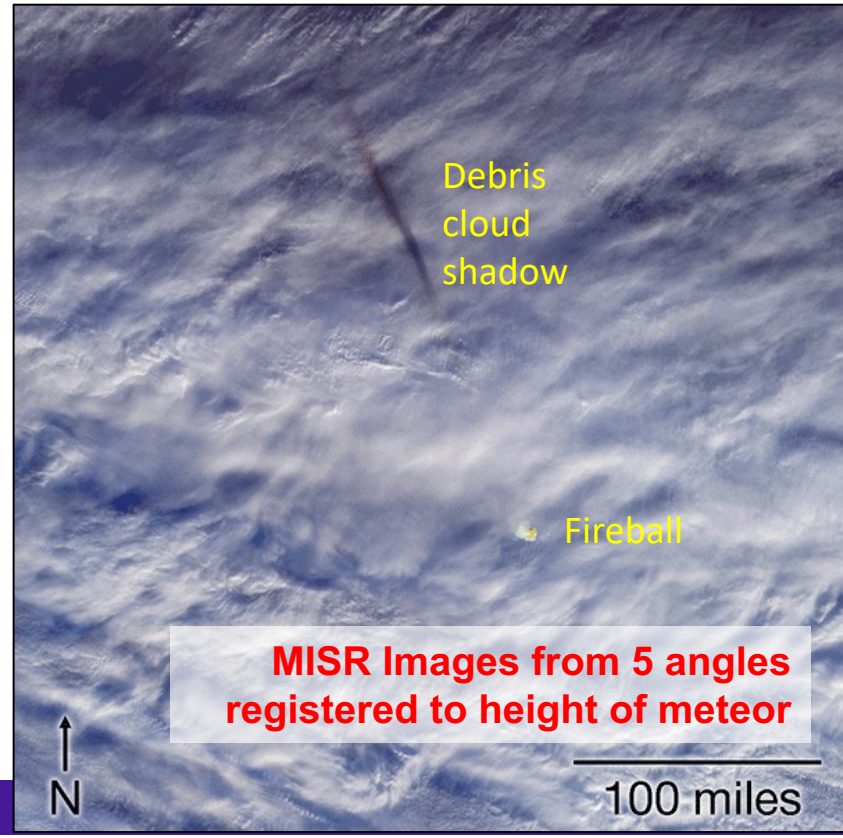
- 2020 Senior Review - “Terra is the most important Earth Observation mission of the 21st century”
- 23-Year Anniversary is December 18
- Terra met the original 18-year data record that was planned for the original three EOS AM platforms



Dec. 18, 2018 "fireball“ over Bering Sea

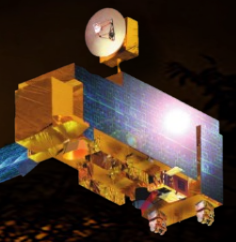
SCIENCE 03/25/2019 11:44 am ET HUFFPOST

NASA Captured Images Of A Giant Meteor Explosion Over Earth



Integrated Science Example
FIRES WORLDWIDE

TERRA

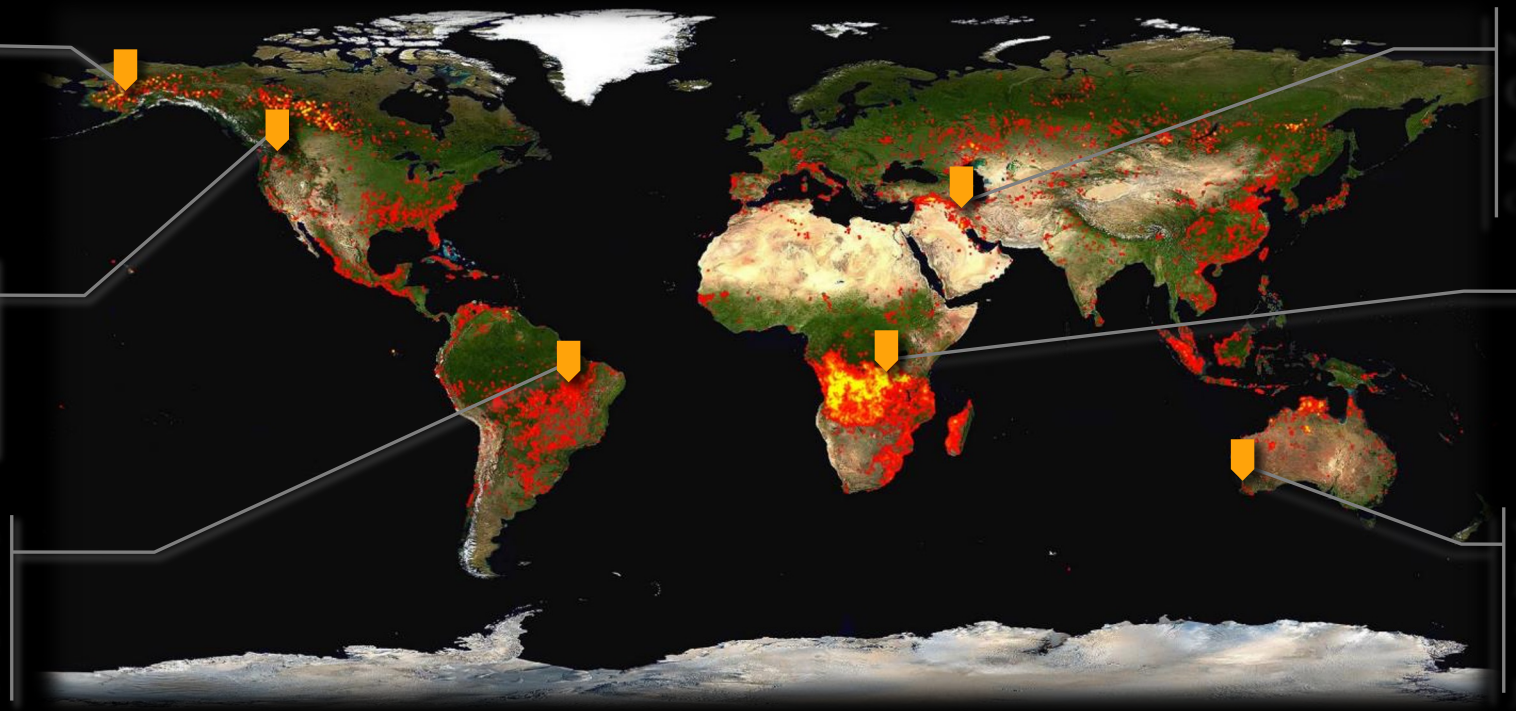


Terra's suite of instruments work together, gathering data to directly benefit citizens around the world. Wildfires are monitored in near real-time, allowing land managers to monitor wildfire progress in the most remote and most urban places, making it possible to warn people in their path. Through estimating burned areas and emissions, recovery efforts are streamlined. Particles and hazardous gasses are tracked as they travel through our atmosphere and transported through the air, impacting people hundreds of miles away by the effects on air quality. MODIS, MISR, ASTER and MOPITT on Terra are crucial to wildfire safety and research.

Alaska, USA
Lightning
5 million acres
June, 2015

Washington, USA
Lightning
1.1 million acres
June –September 2015

South America
Agricultural burning emits
37 Tg of CO
Annually*



Northern Iraq
Oil and Sulfur Fire
4.5 km smoke height
October, 2016**

Central Africa
Agricultural burning
87 Tg of CO
Annually*

Yarloop, Australia
Lightning
170,000 acres
January, 2016

The map shows Global wildfires from June 20th through June 29th, 2015. The fires in Alaska burned over 5 million acres. On June 19th, 2015 a series of 3-day lightning events cascaded into 36,000 lightning events , which attributed to 99.5% of the acreage burned in Alaska. Later that season the state of Washington experienced one of its largest wildfire in state history with over 1.1 million acres burned between June and September. Terra data monitors active fires and the extent of burned areas in even the remotest regions of the world from Alaska to the Australian Bush.

IMAGE SOURCE: Fire maps created by Jacques Descloitres. Fire detection algorithm developed by Louis Giglio. Blue Marble background image created by Reto Stokli

*agricultural burning is one of the primary contributors to wildfires in these regions, numbers based off of MOPITT data from 2001 - 2015

** Data from R. Kahn, T. Kucsera / NASA GSFC, T. Canty, R. Bolt, CJ Vernon / U. Maryland (AAP Project)

Terra has been a healthy platform

- Show key hardware elements and current status
- Nearly all subsystems on primary hardware
- Four non-green items:
  - ASTER SWIR is off
  - Solar array is at 88% capability
  - Batteries are at 77%
  - X-band antenna at 75%

Subsystem	Component	Design	Current	Capability	Comments
EPS	Solar Array	24 Shunts	**21 Shunts**	**88%**	No impact to operations. Additional failures will require reducing load or EPS configuration change. Fully capable of supporting mission thru 2027 unless multiple future failures occur
	Batteries	108 Cells	107 Cells	99%	BBAT cell #50 failed on 10/15/09.
	Batteries	36 Heater Controls	28 Heater Controls	77%	BBAT heater control failed on 4 of 9 heater groups on primary, redundant, and survival. Battery cell charging/discharging and the remaining heater groups are preventing cells from freezing. PBAT heater control performance is nominal.
TCS	MOPITTCPHTS	2	2	Full	Performance is nominal
	SWIR CPHTS	2	2	Full	Performance is nominal
	TIR CPHTS	2	2	Full	Random temperature fluctuations. Performance within requirements.
SCC	SCC	2	2	Full	Performance is nominal
COMM	HGA	2	2	Full	MDA BITE failures occur 2-3/week due to SEU. Recoverable
	X-Band	2	1	75%	DAS Modulator 1 failed (50%). Solid State Power Amplifier redundancy still available (100%).
	CTIU	2	2	Full	Performance is nominal
	OMNI	2	2	Full	Performance is nominal
CDH	MO	2	2	Full	Drift rate changes have occurred since 10/3/10. Performance is within requirements.
	SFE	2	2	Full	SFE SEU occur 1-2/year. Recoverable
	SSR	59 PWA	**59 PWA**	**100%**	Successful SSR Reset on 09/22/21 recovered all 15 previously offline Printed Wire Assemblies
GNC	IRU	3	**2**	Full	Performance is nominal. IRU-B powered off. Yaw axis still redundant.
	TAM	2	2	Full	Performance is nominal
	SSST	2	2	Full	Minor loss of sensitivity in SSSTs – tracker biases updated
	CSS	2	2	Full	Performance is nominal
	ESA	2	2	Full	Performance is nominal
	FSS	1	1	Full	Performance is nominal. Not currently used
	RWA	4	4	Full	Performance is nominal. 3 for 4 redundancy
	MTR	3	3	Full	Performance is nominal
Prop	REAs	16	16	Full	Performance is nominal
Instruments	ASTER - SWIR	2	2	0%	Cooler is unable to maintain detector temperature. Science Data is unusable (Fully Saturated) and is no longer being recorded. Still collecting and monitoring Engineering data.
	ASTER - TIR	2	2	Full	Performance is nominal
	ASTER - VNIR	2	2	Full	Performance is nominal
	CERES - Aft	1	1	Full	Performance is nominal
	CERES - Fore	1	1	Full	Performance is nominal
	MISR	2	2	Full	Performance is nominal
	MODIS	2	1	50%	Power Supply #2 failed, Formatter A degraded, cross-strapped. **All Science is nominal.**
	MOPITT	2	1	50%	Displacer B and Chopper Motor failed. **Loss of redundancy only. All Science is nominal.**

Operations Team reset Terra's Solid State Recorder

Pre-reset buffer allocations

KEY
LRS
MISR
MODIS
ASTER
TRASH
BAD

DMU-1				DMU-2			
Backplane-A		Backplane-B		Backplane-A		Backplane-B	
PWA#	Superset	PWA#	Superset	PWA#	Superset	PWA#	Superset
PWA-2	2	PWA-17	32	PWA-31	60	PWA-46	90
	3		33		61		91
PWA-3	4	PWA-18	34	PWA-32	62	PWA-47	92
	5		35		63		93
PWA-4	6	PWA-19	36	PWA-33	64	PWA-48	94
	7		37		65		95
PWA-5	8	PWA-20	38	PWA-34	66	PWA-49	96
	9		39		67		97
PWA-6	10	PWA-21	40	PWA-35	68	PWA-50	98
	11		41		69		99
PWA-7	12	PWA-22	42	PWA-36	70	PWA-51	100
	13		43		71		101
PWA-8	14	PWA-23	44	PWA-37	72	PWA-52	102
	15		45		73		103
PWA-9	16	PWA-24	46	PWA-38	74	PWA-53	104
	17		47		75		105
PWA-10	18	PWA-25	48	PWA-39	76	PWA-54	106
	19		49		77		107
PWA-11	20	PWA-26	50	PWA-40	78	PWA-55	108
	21		51		79		109
PWA-12	22	PWA-27	52	PWA-41	80	PWA-56	110
	23		53		81		111
PWA-13	24	PWA-28	54	PWA-42	82	PWA-57	112
	25		55		83		113
PWA-14	26	PWA-29	56	PWA-43	84	PWA-58	114
	27		57		85		115
PWA-15	28	PWA-30	58	PWA-44	86	PWA-59	116
	29		59		87		117
PWA-16	30			PWA-45	88		
	31				89		

MODIS	26
MISR	15
ASTER	42
LRS	1
Trash	0

Before vs After Reset

No red means great!

Terra onboard data storage has been returned to its original full capability

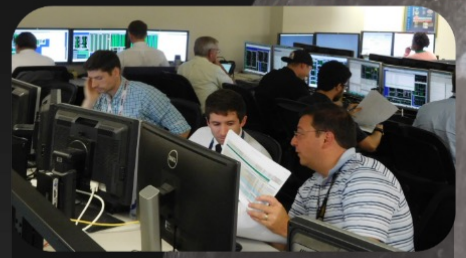
Post-reset allocation (all buffers recovered)

KEY
LRS
MISR
MODIS
ASTER
TRASH
BAD

DMU-1				DMU-2			
Backplane-A		Backplane-B		Backplane-A		Backplane-B	
PWA#	Superset	PWA#	Superset	PWA#	Superset	PWA#	Superset
PWA-2	2	PWA-17	32	PWA-31	60	PWA-46	90
	3		33		61		91
PWA-3	4	PWA-18	34	PWA-32	62	PWA-47	92
	5		35		63		93
PWA-4	6	PWA-19	36	PWA-33	64	PWA-48	94
	7		37		65		95
PWA-5	8	PWA-20	38	PWA-34	66	PWA-49	96
	9		39		67		97
PWA-6	10	PWA-21	40	PWA-35	68	PWA-50	98
	11		41		69		99
PWA-7	12	PWA-22	42	PWA-36	70	PWA-51	100
	13		43		71		101
PWA-8	14	PWA-23	44	PWA-37	72	PWA-52	102
	15		45		73		103
PWA-9	16	PWA-24	46	PWA-38	74	PWA-53	104
	17		47		75		105
PWA-10	18	PWA-25	48	PWA-39	76	PWA-54	106
	19		49		77		107
PWA-11	20	PWA-26	50	PWA-40	78	PWA-55	108
	21		51		79		109
PWA-12	22	PWA-27	52	PWA-41	80	PWA-56	110
	23		53		81		111
PWA-13	24	PWA-28	54	PWA-42	82	PWA-57	112
	25		55		83		113
PWA-14	26	PWA-29	56	PWA-43	84	PWA-58	114
	27		57		85		115
PWA-15	28	PWA-30	58	PWA-44	86	PWA-59	116
	29		59		87		117
PWA-16	30			PWA-45	88		
	31				89		

MODIS	36
MISR	22
ASTER	57
LRS	1
Trash	0

Terra flipping for science – An example of operations and data quality

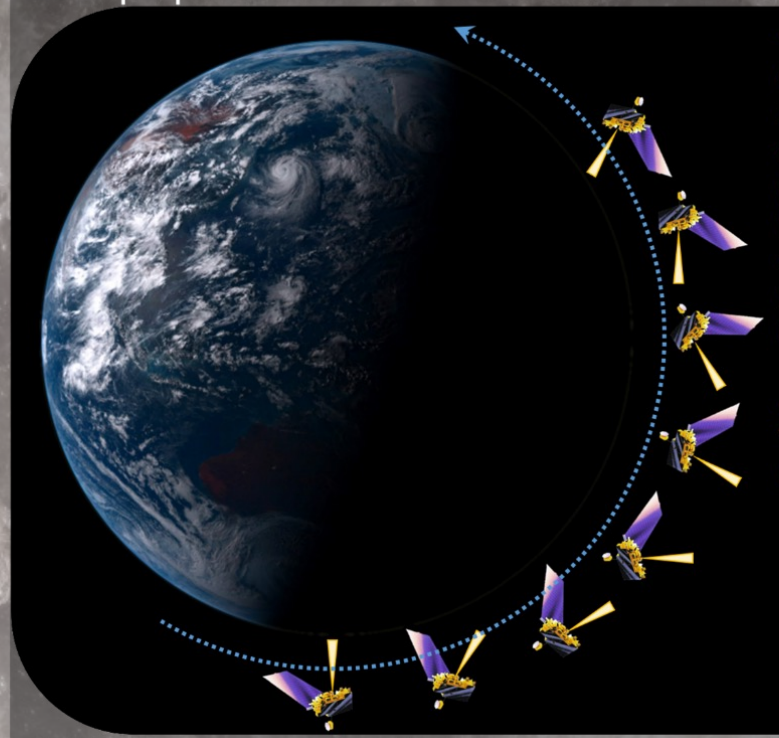


"The Moon is like a standard candle or lamp: the amount of energy from it is well known, if you look at it periodically, it allows you to see if your instruments are changing over time."

-Kurt Thome, Terra Project Scientist

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was corrected to account for Terra's motion and distance to the moon during the maneuver and compared with predictions (above) and results from the 2003 maneuver (below).

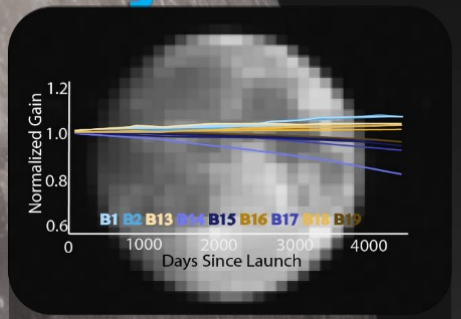
After three years of discussion, planning and preparations, Terra's flight operations team successfully executed a Lunar Deep Space Calibration maneuver on Aug. 5, 2017.



"The Lunar deep space calibration maneuver requires pitching the spacecraft a complete 360 degrees during spacecraft night, while precisely scanning the moon at a fixed rate through the center of instruments' fields of view."

- Dimitrios Mantziaras, Terra Earth Science Mission Operations Director

This complex and risky maneuver allowed the mission team to recalibrate Terra's imagers, improving instrument accuracy and providing data to calibrate other satellites.



The Moderate Imaging Spectro-radiometer (MODIS) looks to the moon monthly to continuously calibrate its sensors. The different bands and their corrections are noted in the graph in the foreground. The background image is the MODIS image of the moon from the 2017 August 5 lunar deep space calibration maneuver.

MISR, the Multi-angle Imaging Spectroradiometer, has nine cameras that image Earth from different angles. This image shows the moon from three of the nine cameras. During the lunar maneuver, each camera saw the almost-full Moon straight on. This means that the different focal lengths produced images with different resolutions.

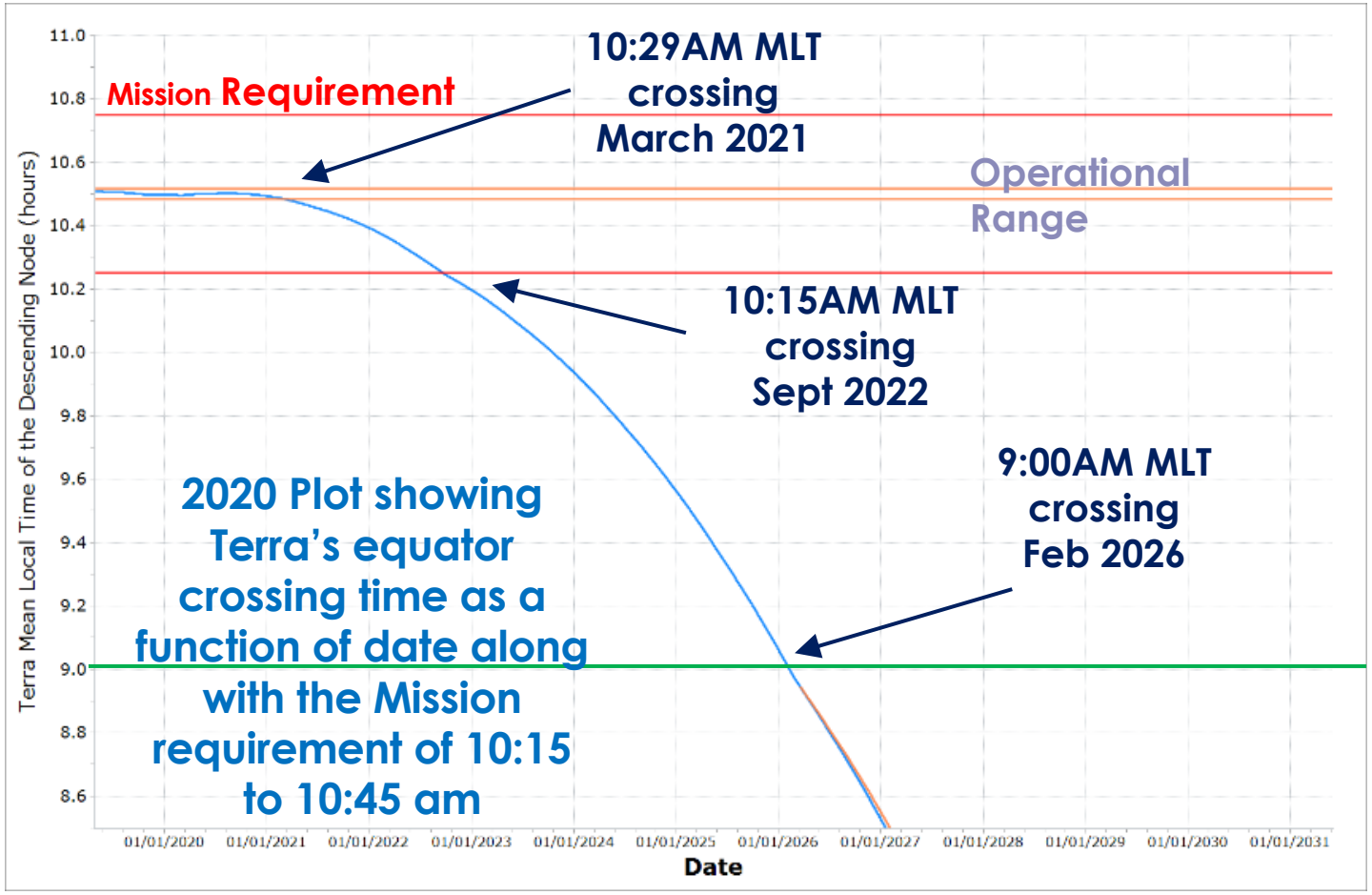
Operations, Fuel Use, and Orbital Impacts to Science

Studies and reviews that took place from 2014-2017 helped evaluate orbital scenarios and fuel use

- Maintaining MLT to ±1 min was found to make the best use of Terra's data record
- Additional months of observations at the 10:30 MLT were determined to be invaluable to climate trend studies
  - Change in MLT would have limited the full potential of Terra's "climate quality" data record for trend analysis
  - Added record length increased ability to detect significant long-term (climate) trends
- Received approval from NASA Headquarters to continue usage of inclination maneuvers to maintain MLT

Where (and When) has Terra been?

Led to continuing inclination adjust maneuvers until February 27, 2020

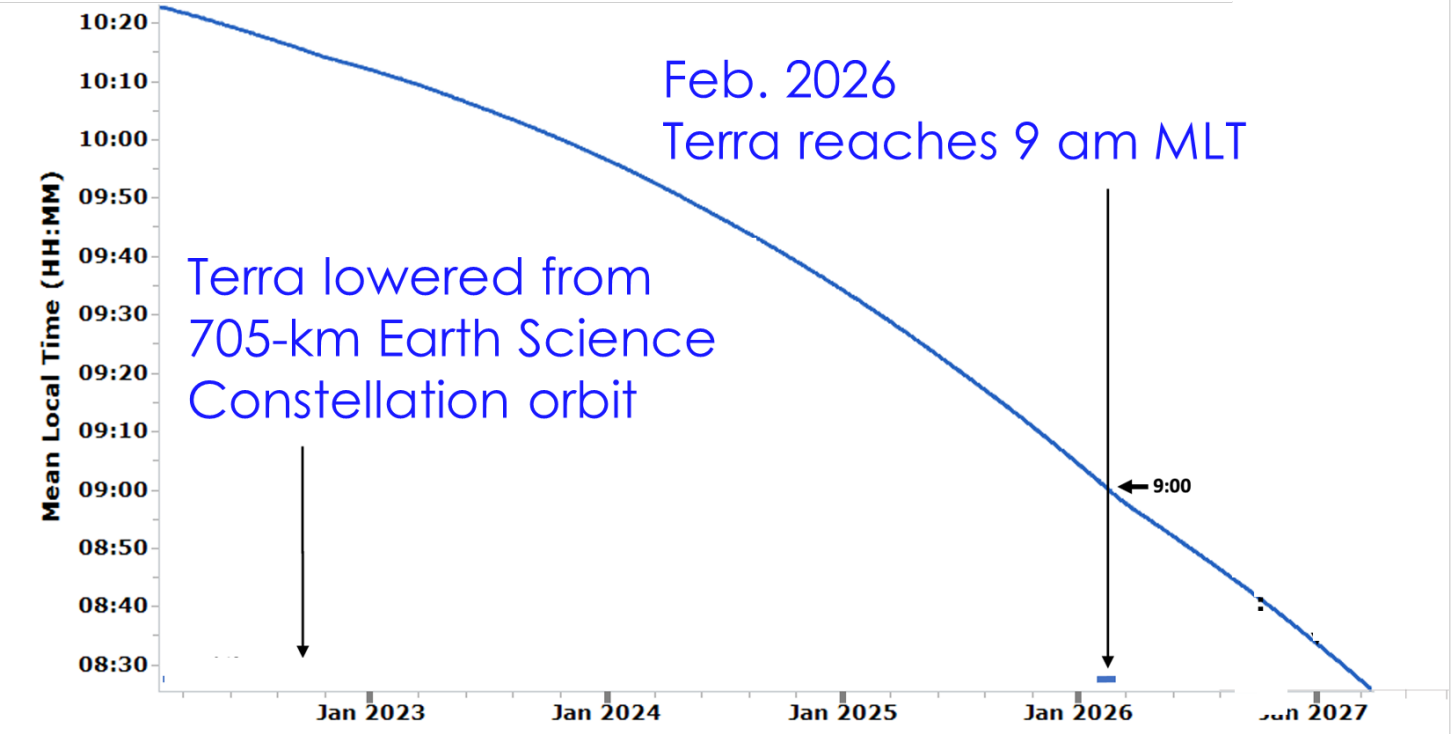


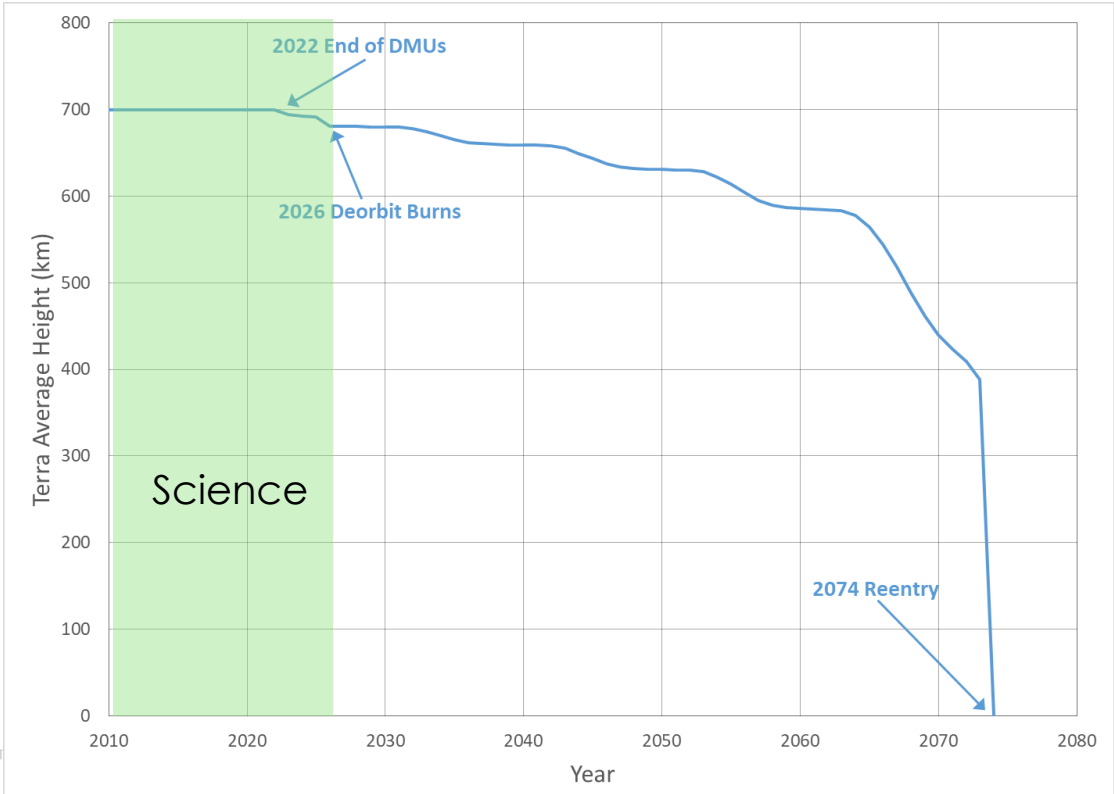
- Maintained both crossing time and platform altitude to provide highest quality data
  - Inclination maneuvers controlled platform's mean local time (MLT) of equator crossing
  - Held 10:30 am crossing time for >20 years
  - Drag makeup maneuvers used to maintain Terra's 705-km altitude
  - Risk mitigation maneuvers to avoid orbital debris are also continuing
- Crossing time has slowly been changing to an earlier time

Where (and when) was Terra in October?

Reached the 10:15 am crossing time requirement in September 2022 while still at 705-km altitude orbit

- Drag makeup maneuvers were continued to be used to maintain Terra's altitude
  - Ensured repeatable ground track
  - Kept Terra on WRS-2 (worldwide reference system) with its 16-day repeat
- Risk mitigation maneuvers for orbital debris avoidance





Orbital impacts to science

Terra began as a process-oriented mission and all products are valid for process studies as Terra's orbit changes

- Long data record allows Terra data to be used to evaluate climate trends
- 20-year record at tight 2-minute MLT crossing allows insight into how a drifting orbit impacts long-term datasets and data continuity
  - MLT drift does not cause degradation of Terra data product quality
  - Initial 2 years at 10:45 am MLT provides additional data point
- Orbital altitude does not impact L1 radiometric quality but does affect ground track
  - Geometric corrections changed to account for altitude changes
  - Will be changes in spatial sampling

Previous studies also pointed towards new science

2017 Panel Review evaluated possible benefits from new observing conditions to generate novel science

- That review still concluded that maintaining Terra's MLT was more important
- Earlier crossing times pointed towards
  - Improved evaluation of volcanoes due to larger thermal contrasts and fewer clouds
  - Thermal-physical studies in land and vegetation processes
  - Evaluating temporal modeling of physical parameters
  - Understanding solar angle effects
  - Temporal effects on aerosols, pollution, fires, vegetation, and clouds
- Many of the above were also captured as part of the recent Workshop held to evaluate the drifting orbits of Terra, Aqua, and Aura

Summary

Success of Terra has been due to the collaborative efforts of the instrument, platform, and flight operations teams coupled to the science users and data providers.

- Rest of the forum will demonstrate this by hearing from the
  - Flight Operations Team's efforts to organize and implement the Constellation Exit Maneuver
  - Instrument status from each of the teams including discussions of possible data impacts from the orbit lowering
- Finish with a what's next for Terra

Terra Orbit Lowering
Constellation Exits and Beyond

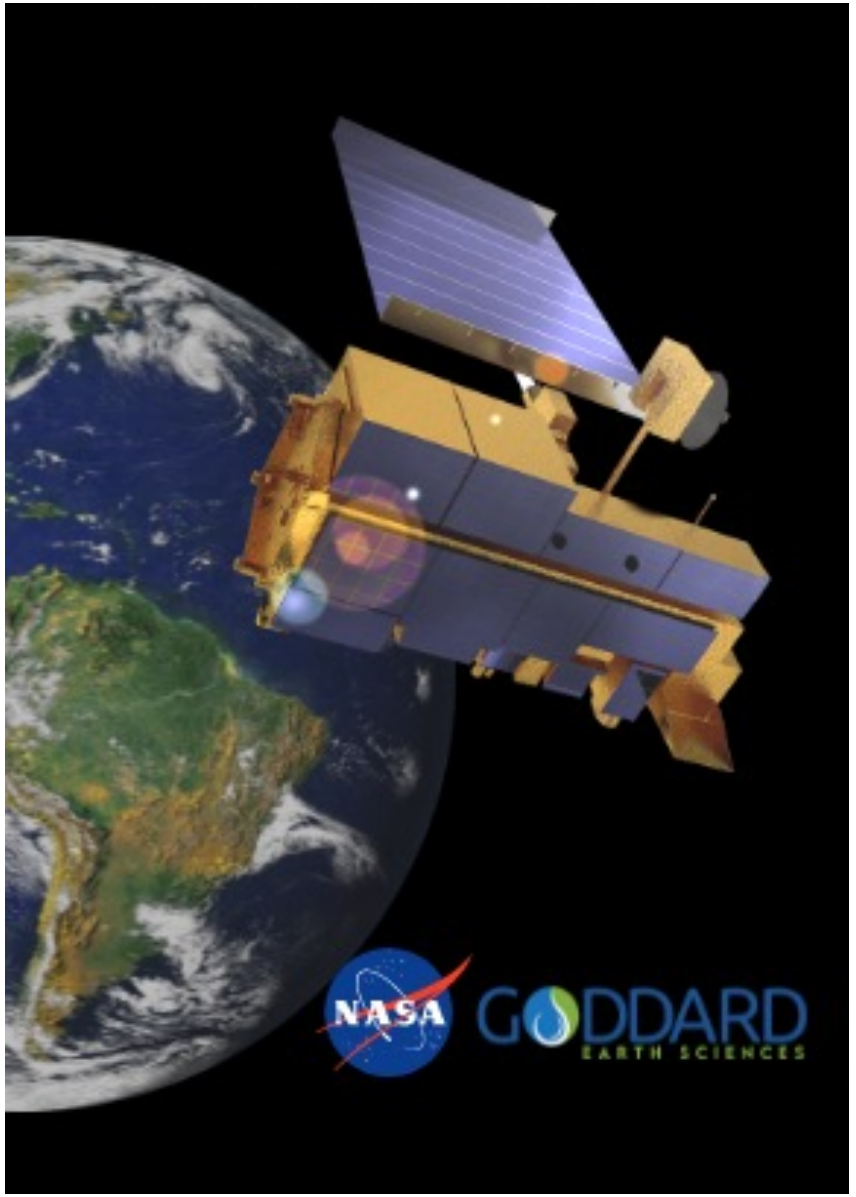
Jason Hendrickson,

Terra Flight Systems Manager

Jason.T.Hendrickson@nasa.gov

Agenda

- **Terra Mission Overview**
- **Background**
  - Terra Fuel History
  - Mean Local Time (MLT) History
- **Constellation Exit Maneuvers (CEM)**
  - Constellation Exit Maneuver Pair
  - CEM Instrument Configuration
  - CEM Planning and Preparation
  - CEM Results
- **Future Orbit**
  - Expected Orbital Changes
  - Predicted Mean Local Time
  - Terra Lifetime : Altitude prediction
- **Conclusions**



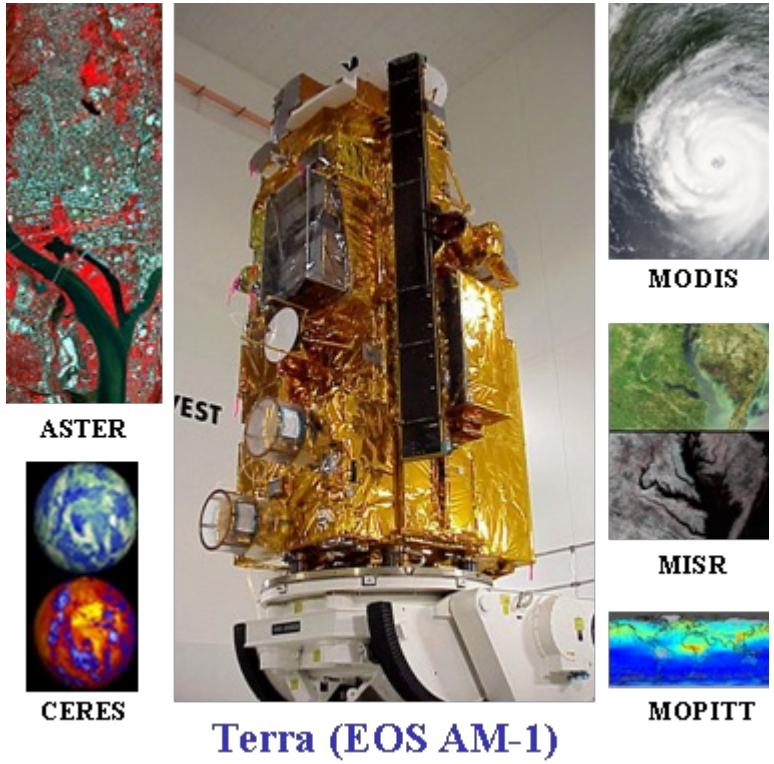
Terra Mission Overview

Terra Features

- **Launch Date:** *December 18,1999 (Atlas IIAS, VAFB)*
- **Original Orbit:** *705 km, Sun-synchronous polar, 98.2° Inclination, 10:30 AM MLT descending node*
- **Instrument Payload:**
  - **ASTER (*SWIR*, TIR & VNIR) -** *Advanced Spaceborne Thermal Emission and Reflection Radiometer* (Japan)
  - **CERES (Fore & Aft) -** *Clouds and the Earth's Radiant Energy System* (USA – Langley)
  - **MISR -** *Multi-angle Imaging Spectro-Radiometer* (USA – JPL)
  - **MODIS -** *Moderate Resolution Imaging Spectro-radiometer* (USA – GSFC)
  - **MOPITT -** *Measurement of Pollution in the Troposphere* (Canada)
- **Project Management:** *Earth Science Mission Operations (ESMO)*
- **Spacecraft Flight Operations:** *Contracted by GSFC to KBR team and supported by NASA NENs and TDRSS*
- **Instrument Operations and Science Data processing:** *Performed at respective Instrument Locations where developed*
- **Mission Duration:** *Successfully completed Prime mission of 5 years. Currently in Extended Operations.*
- **Distributed Active Archive Centers:** *LP DAAC – MODIS, ASTER; Langley DAAC – CERES, MISR, MOPITT*

Science

- *The primary objective of the Terra Mission is to simultaneously study clouds, water vapor, aerosol, trace gases, land surface and oceanic properties, as well as the interaction between them and their effect on the Earth's energy budget and climate.*

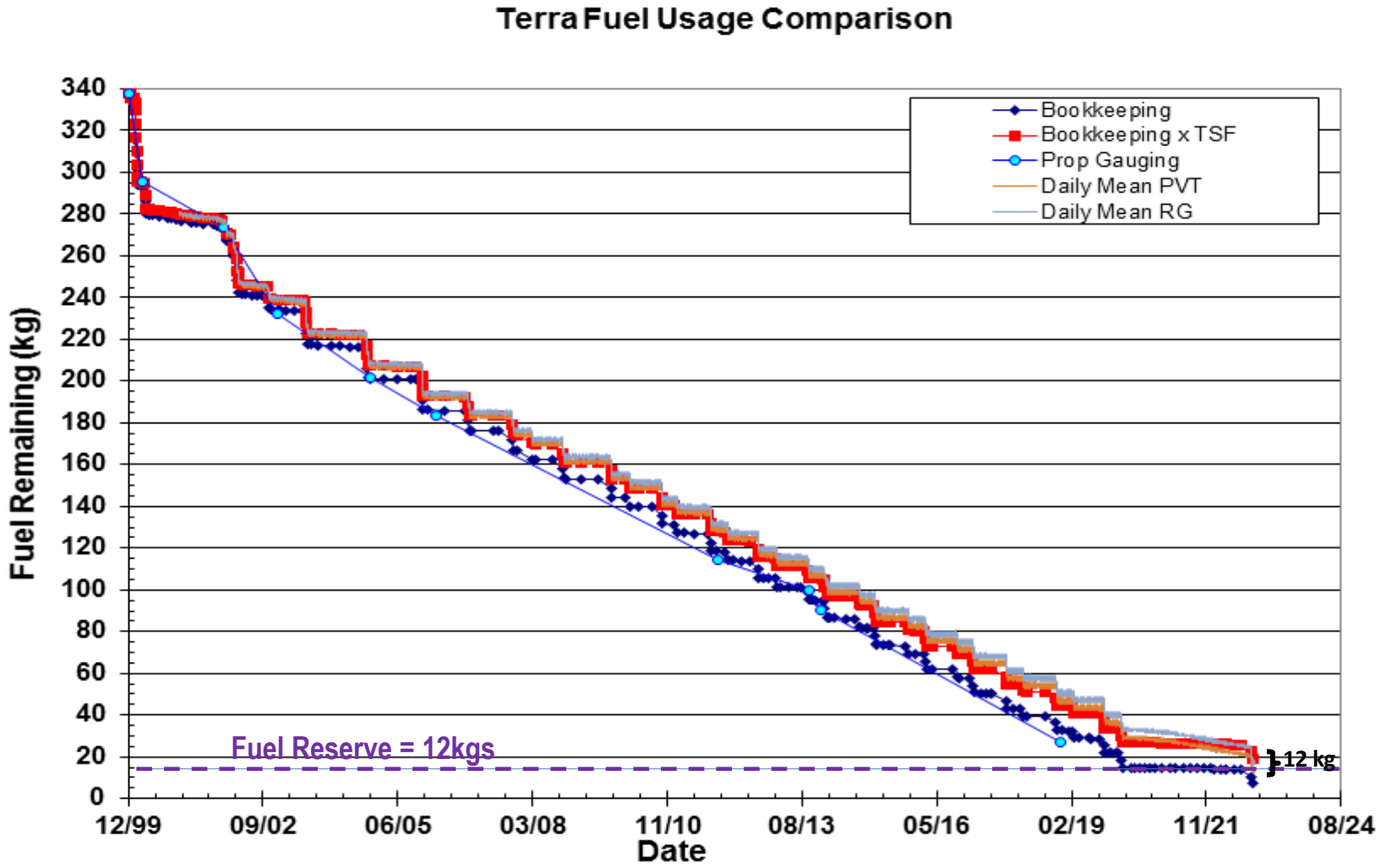


Background

- **Terra was launched with 340 kg of fuel**
  - Fuel expended over mission to maintain constellation orbit requirements
    - Original Ascent Maneuvers to enter mission orbit
    - Inclination Adjust Maneuver (IAM)
      - Large burns to maintain Mean Local Time (MLT)
    - Drag Make-up maneuvers (DMU) & Risk Mitigation Maneuvers (RMM)
      - Small burns to maintain Ground Track Error (GTE)
      - Some fuel also used to avoid debris when necessary (RMMs)

- **Reserved fuel to ensure safe exit of constellation with Landsat, Aqua, Aura, etc.**
  - Final Inclination Adjust Maneuvers – Feb. 2020
  - When Terra was no longer within original orbit requirements Terra exited the constellation – Oct. 2022

Terra Fuel History

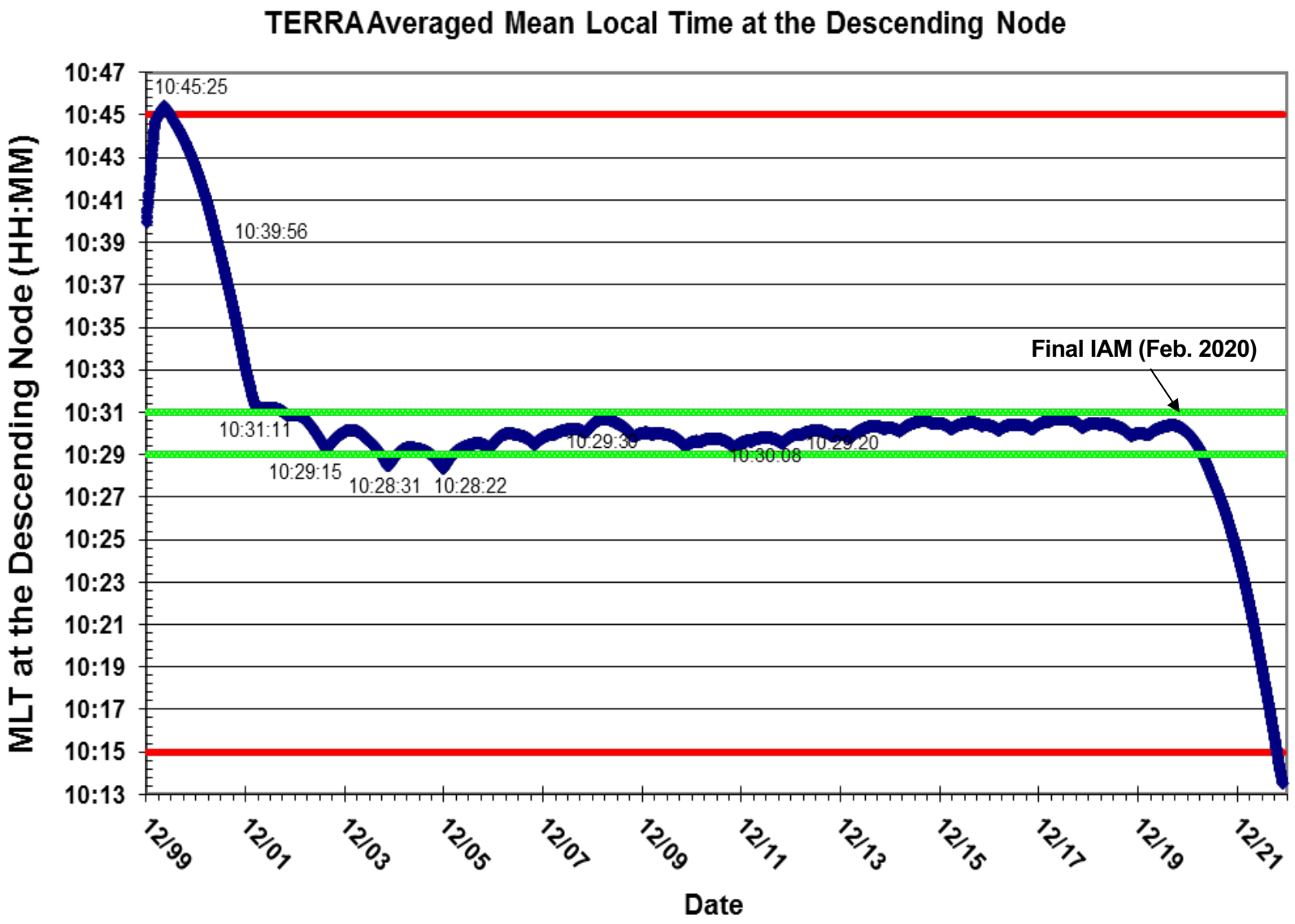


12 kg of fuel reserved to safely exit satellite constellation envelope

Required for 2 Retrograde burns (~4 kg each) plus unusable fuel trapped in lines (max ~3.9 kg)

Due to uncertainties in estimating remaining fuel multiple methods were used
Most conservative methodology used to guide constellation exit planning

Mean Local Time History



Constellation Exit triggered when Terra reached 10:15 am MLT limit

Original Requirement: MLT 10:15 am – 10:45 am
Operational Range : MLT 10:29 am – 10:31 am

CONSTELLATION EXIT MANEUVERS

Why Exit the Constellation?

- **The Constellation members flying together agreed to maintain their orbits within mission requirements**

- **Missions agreed to maintain a list of trigger events that lead to Constellation Exit for safety of all members**
  - Deviating from agreed orbit parameters increases risks of close approaches with other constellation members and requires more communication
  - Since constellation orbits are “frozen” an envelope identifies safe exit distance

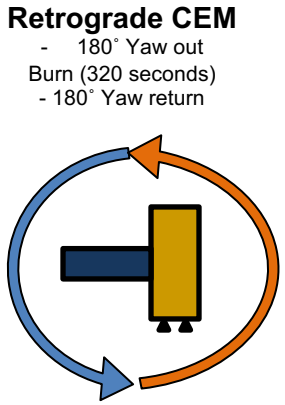
- **Triggers for Terra Constellation Exit include**
  - Hardware Failure that could prevent safe constellation flying
    - Terra’s hardware is still healthy, on all prime hardware
  - Insufficient fuel to maintain constellation orbit
    - Terra reserved 12 kg for Exit

- **Reaching Terra’s reserve fuel estimate triggered a Constellation Exit due to lack of fuel**
  - Fuel required to maintain orbit
  - Terra was lowered a safe distance from other constellation members

- **Terra’s hardware is healthy and continues to collect excellent science data**
  - Includes excellent science opportunities at the lower altitude

Constellation Exit Maneuvers

- **In October 2022 Terra Executed 2 Constellation Exit Maneuvers (CEMs)**
  - Each CEM Terra turned 180° before activating thrusters for 320 secs
    - Slew out and back to 180° took ~17 mins. 13 seconds each
    - Retrograde Maneuver
  - CEM #1 executed on October 12, 2022 during spacecraft night
  - CEM #2 executed on October 19, 2022 during spacecraft day

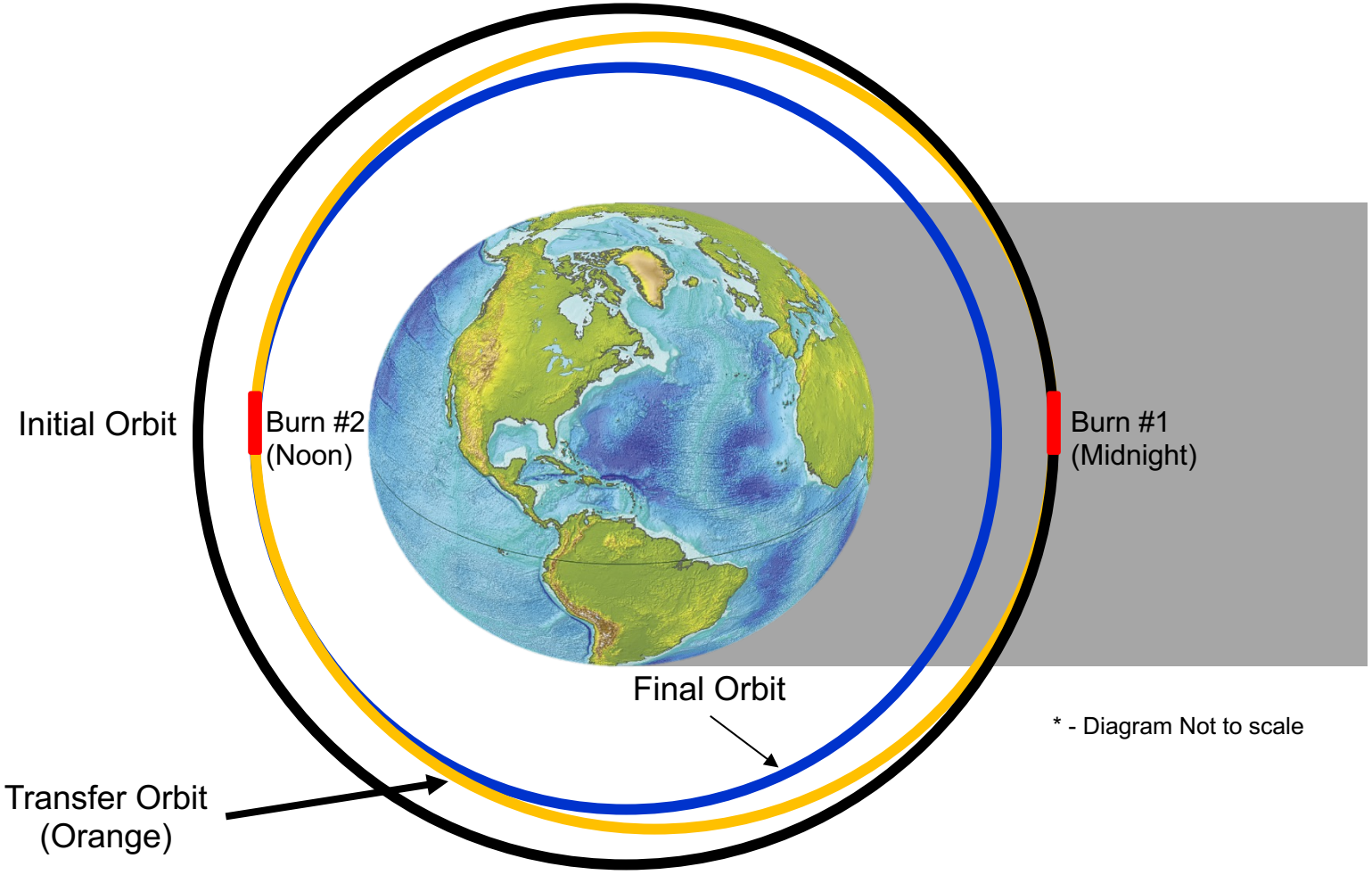


- **The Constellation Exit Maneuvers lowered Terra's orbit by ~5.5 km**
  - By lowering 5.5 km Terra safely left the morning and afternoon constellation envelopes
    - Morning Constellation : Terra, Landsat 8, Landsat 9
    - Afternoon Constellation : Aqua, Aura, GCOM-W1 and OCO-2
  - The maneuver pair maintained a circular orbit at the lower altitude

Constellation Exit Maneuver Pair (Oct. 12 & 19, 2022)

Constellation Exit done in a pair to maintain frozen/circular orbit

- One executed during S/C Noon and the other during S/C Midnight
  - Opposite Sides of Orbit
- Frozen minimizes Science impacts from variation orbit
- Keeps Terra safely spaced from constellation as orbit decays



CEM – Instrument Configurations

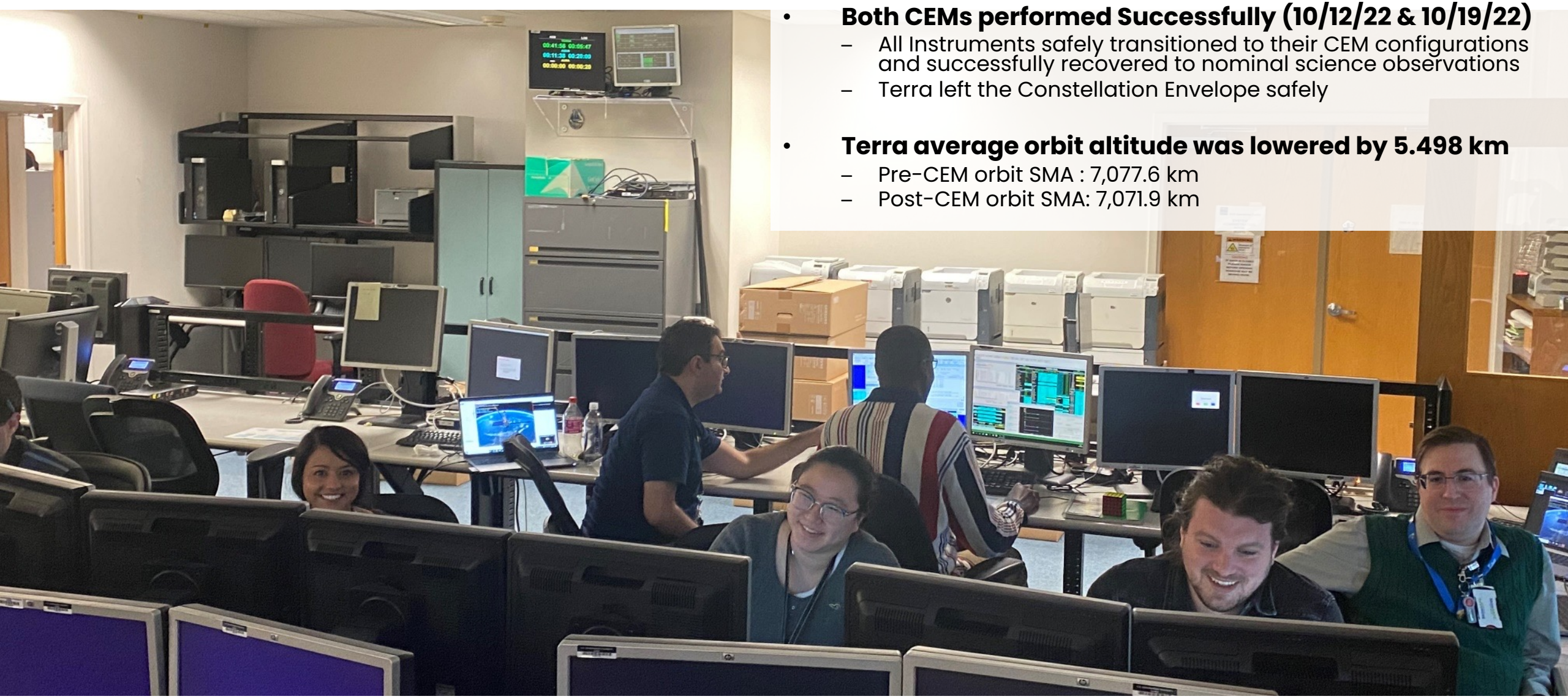
IOT	IAM Configuration (Routinely executed yearly until 2020)	Retro Configuration	Science Outage Period
MODIS	**Remain in Science Night Mode** Contingency-only Door Close inhibited if slew return successful	**Remain in Science Night Mode** Abnormal Data Flag set Space View & Nadir doors closed Non-essential components powered off	10/10/22 – 10/21/22
MISR	**Taxi-Off Mode**	**Taxi-Off Mode** (Same as IAM)	Few Orbits around Maneuver 10/12/22 & 10/19/22
CERES	**CONTAM Safe for both CEA and CEF**	**CONTAM Safe for both CEA and CEF** (Same as IAM)	Few Orbits around Maneuver 10/12/22 & 10/19/22
MOPITT	**Science Mode**	**Safe Mode** Hot Calibrations before and after CEMs	10/10/22 – 10/26/22 : MOPITT Safe Only 10/03/22 – 10/28/22 : including Hot Cals
ASTER	**Standby Operational Mode**	**Contamination Safe Mode:** Same as normal standby operational mode but with TIR mirror parked in Cal position	10/12/22 – 10/20/22

CEM Planning and Preparation

- **FOT Developed the original CEM process in 2019**
  - In 2022 the FOT updated the CEM process and refreshed the FOT members on the process
- **Consulted with spacecraft manufacturer (LMCO)**
- **Held independent review with other mission operations teams**
- **Coordinated with each IOT to determine best configuration for the CEM**
- **Conducted dozens of nominal and contingency simulations over 2019 and 2022**
  - 9+ Simulations in 2019 to develop and validate CEM Planning and execution process
  - 11+ Simulations in 2022 to fine tune the CEM process and prepare FOT for the actual execution
    - Simulated using final parameters and timelines expected for October 2022
    - Included simulations of potential CEM contingency

CEM Results

- **Both CEMs performed Successfully (10/12/22 & 10/19/22)**
  - All Instruments safely transitioned to their CEM configurations and successfully recovered to nominal science observations
  - Terra left the Constellation Envelope safely
- **Terra average orbit altitude was lowered by 5.498 km**
  - Pre-CEM orbit SMA : 7,077.6 km
  - Post-CEM orbit SMA: 7,071.9 km



Terra FOT Executing Constellation Exit Maneuver #2 (10/19/22)

FUTURE ORBIT

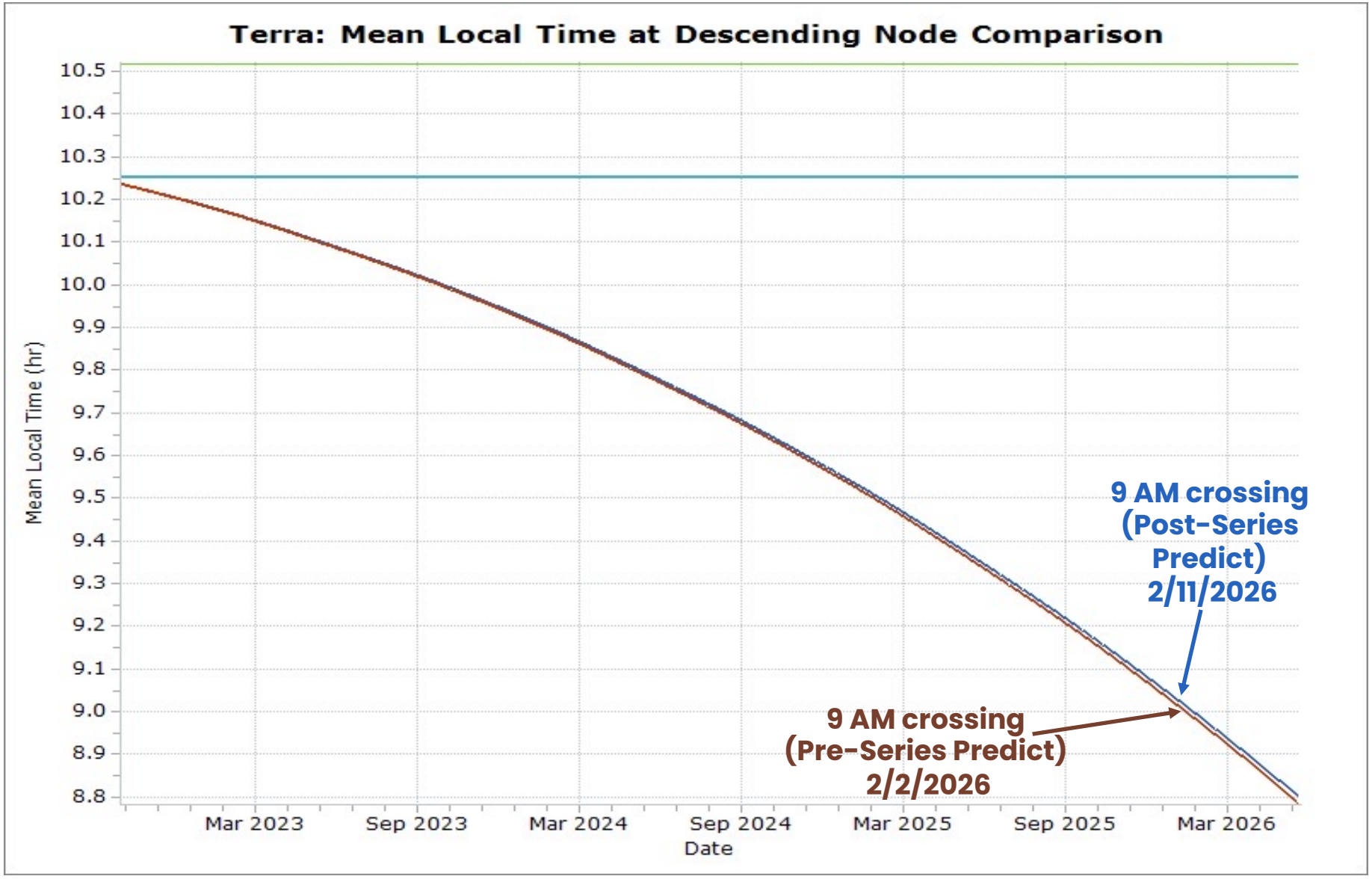
Expected Orbital Changes

- **Terra will no longer maneuver to maintain orbit**
  - Remaining fuel will be saved for debris avoidance and final perigee lowering
  - Terra's orbit will no longer be repeatable and will gradually change over time

- **Mean Local Time will continue to gradually move earlier**
  - Current MLT : ~10:15 am
  - Feb. 2026 MLT : 9:00 am

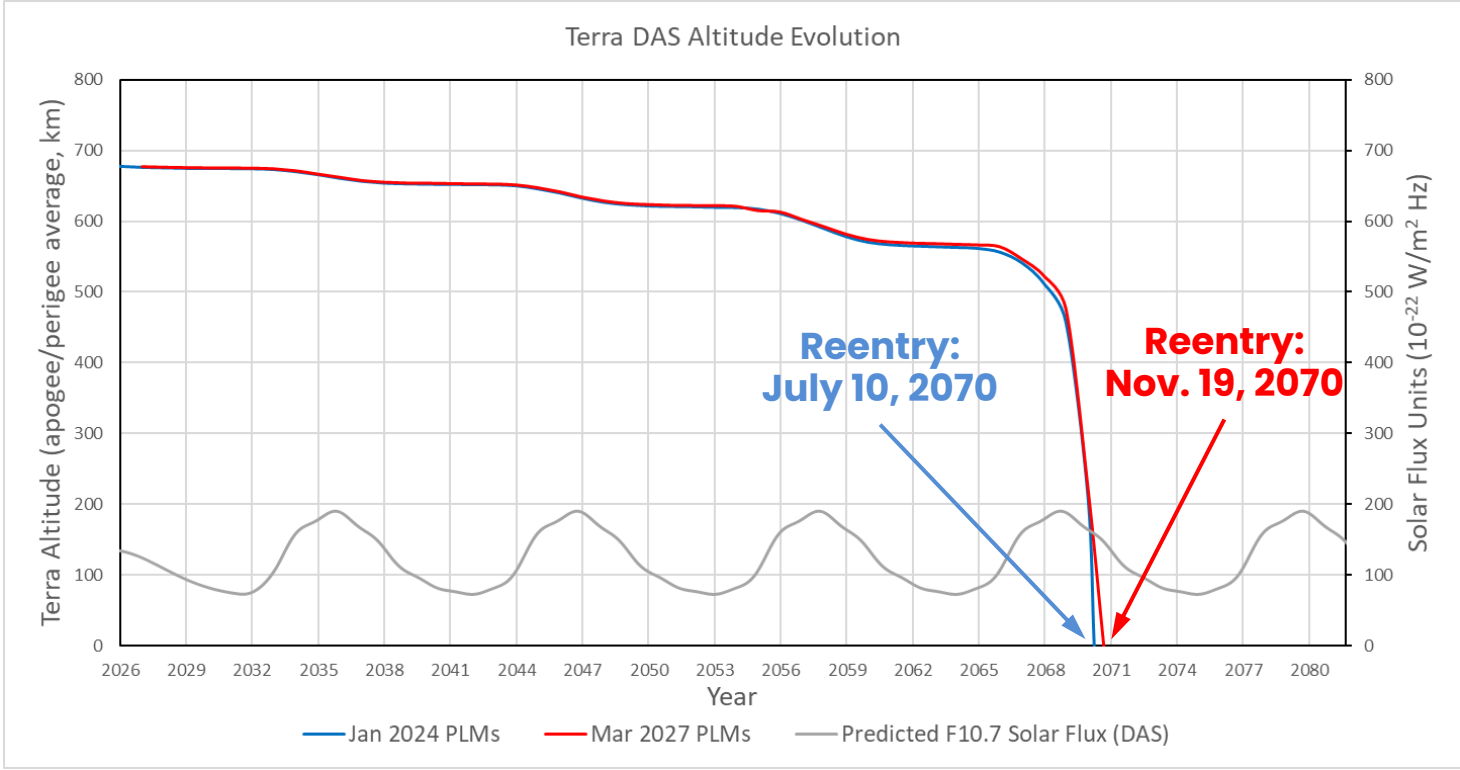
- **Altitude will slowly decrease over time**
  - For first several years we expect altitude to decay by ~1.5 km per year
  - Orbital period will decrease over time
  - Takes us off of the WRS ground track/16-day repeat cycle

Predicted Mean Local Time (through 2026)



Terra Lifetime

Altitude Predictions



Decommissioning Plan	Deorbit Year	De-orbit Burns (#)	Apogee at Depletion (km)	Perigee at Depletion (km)	End of Mission (EOM)	EOM to Reentry (years)	Reentry Date
2024 Deorbit analysis (4 x 320-sec burns + 1 x 32-sec burn)	2024	**5**	699.17	663.52	2024.10	46.42*	2070.52
2027 Deorbit analysis (4 x 320-sec burns + 1 x 32-sec burn)	2027	**5**	696.04	658.76	2027.29	43.60*	2070.89

Updated based on Fall 2022 Lifetime Analysis

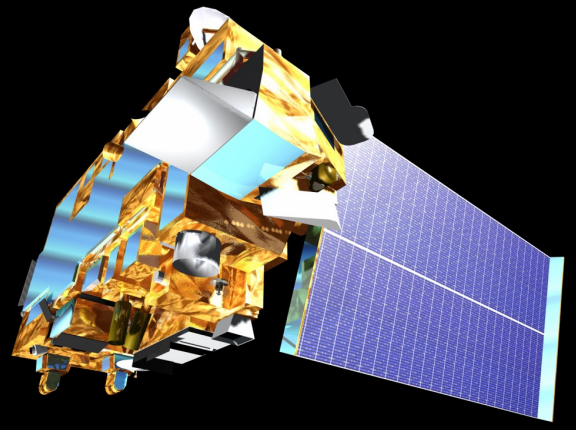
*Note: Terra launched prior to the 25-year re-entry requirement

Conclusions

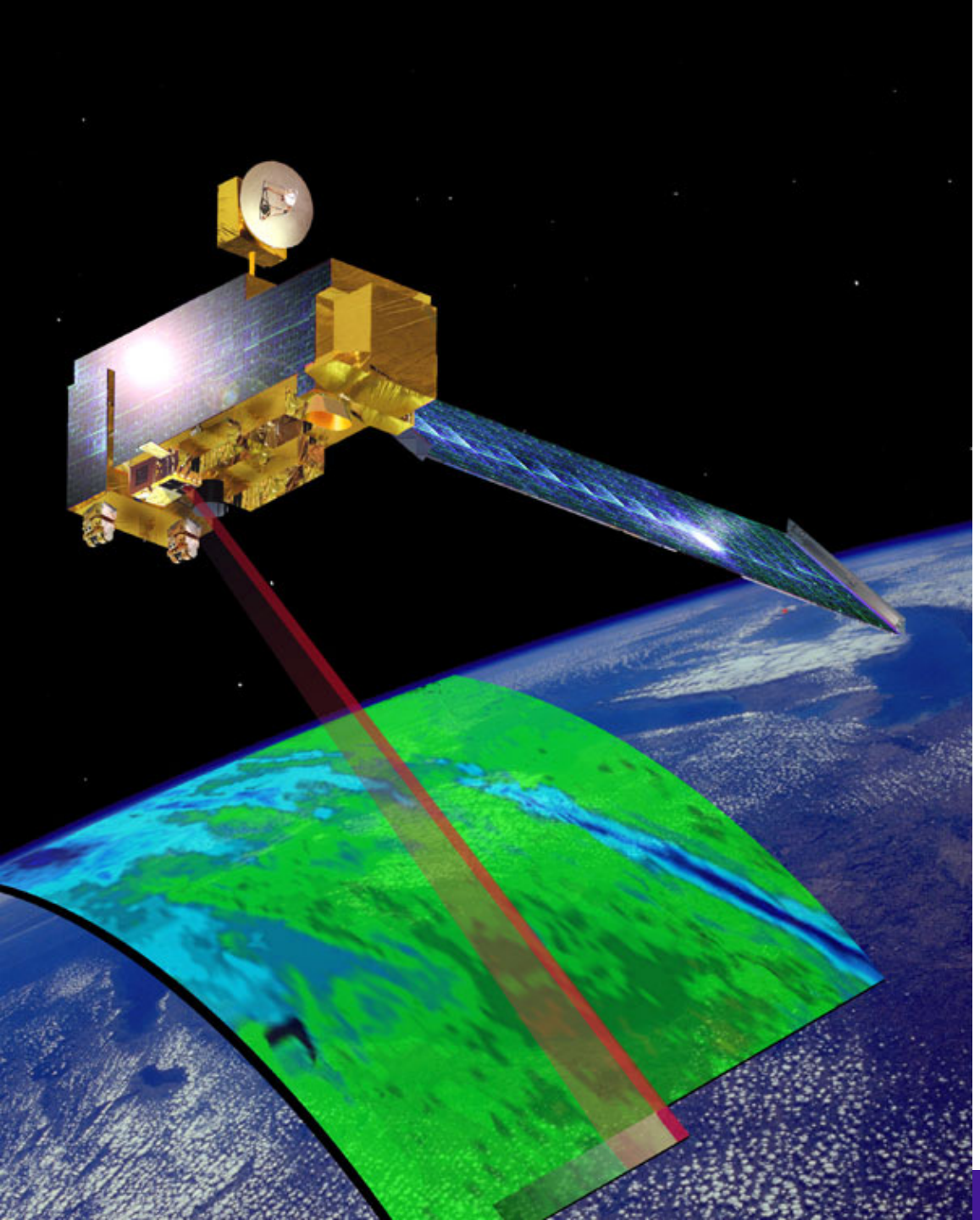
- **Terra hardware continues to be healthy after nearly 23 years on orbit**
- **Constellation Exit Maneuvers Successful**
  - Terra's orbit lowered away from constellation members
- **Orbit will gradually change over time**
  - No longer maintaining a repeatable ground track or MLT
- **Terra continues to be able to collect great science at the lower altitude**
  - Instruments are still healthy and collecting science data
  - Changing orbit introduces opportunities for new observations not possible in old orbit

22 years of MOPITT

- Review of MOPITT science
- Changes with lower orbit
- Continuation of data record



H. Worden, NCAR
J. Drummond, U. Toronto



MOPITT on EOS/Terra

- Uses Gas Filter Correlation Radiometry (GFCR) to measure carbon monoxide (CO) in both thermal and near infrared (TIR+NIR).
- 605 km wide swath gives global coverage in ~3 days with 22 x 22 km^2 pixels.
- CO plays a key role in atmospheric chemistry:
  - Good tracer of pollution (lifetime of weeks to months)
  - Major sink of OH => emissions of CO increase methane lifetime
  - Precursor to tropospheric ozone
  - Emissions of CO have a net climate radiative forcing

WORLDWIDE DATA USERS

Carleton University
Dalhousie University
Environment and Climate Change Canada
University of Toronto
University of Waterloo

14

Argonne National Laboratory
California Institute of Technology
Colorado State University
Columbia University
Duke University
Florida State University
Georgia Institute of Technology
Harvard University
Institute for Marine and Atmospheric Research
NASA Ames Research Center
NASA Goddard Institute for Space Studies
NASA Goddard Space Flight Center
NASA Jet Propulsion Laboratory (JPL)
NASA Langley Research Center
National Center for Atmospheric Research (NCAR)
National Oceanic and Atmospheric Administration (NOAA)
North Carolina State University
Pennsylvania State University
Princeton University
Science Systems and Applications, Inc.
United States Environmental Protection Agency (US EPA)
Universities Space Research Association
University of Alabama in Huntsville
University of Alabama Huntsville
University of Arizona
University of California, Berkeley
University of California, Irvine
University of California, Los Angeles
University of Colorado at Boulder
University of Iowa
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Clarendon Laboratory
Cranfield University
European Centre for Medium-Range Weather Forecasts (ECMWF)
King's College
Lancaster University
Met Office
National Centre for Earth Observation
School of GeoSciences
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University of East Anglia
University of Edinburgh
University of Leeds
University of Leicester
University of Reading
University of York

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Free University
Institute for Environement and Sustainability
Institute for Marine and Atmospheric Research
Royal Netherlands Meteorological Institute (KNMI)
Netherlands Organization for Applied Scientific Research (TNO)
SRON Netherlands Institute for Space Research
Utrecht University
Vrije Universiteit Amsterdam
Wageningen University and Research Centre

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National Institute For Space Research (INPE)
University of São Paulo

CEA Saclay Nuclear Research Centre
Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS)
Direction de la Météorologie Nationale (CNRM)
Institut Pierre Simon Laplace (IPSL), École Polytechnique
Institut Recherche pour le Dévelopement
Laboratoire de Météorologie Dynamique (LMD)
Laboratoire d'Aérologie
Laboratoire des Sciences du Climat et de l'Environnement (LSCE)
Météo France
Mosecomonitoring
Sorbonne University
Université de Paris-Est
Université de La Réunion
Université de Toulouse
Université de Versailles Saint-Quentin-en-Yvelines
Université Paris Saclay
Université Pierre et Marie Curie

Belgian Institute for Space Aeronomy (BIRA-IASB)
Université de Liège
Université libre de Bruxelles (ULB)

Instituto Nacional de Investigacion y Tecnologia Agraria y Alimentaria (INIA)

University of Oslo
Norwegian Institute for Air Research (NILU)

Chalmers University of Technology

German Aerospace Center (DLR)
German Meteorological Service (DWD)
Helmholtz Zentrum Geesthacht (HZG)
Institute for Chemistry and Dynamics of the Geosphere Troposphere
Institute for Environmental Physics
Institute for Meteorology and Climate Research (IMK)
Johannes Gutenberg University
Julich Research Center
Karlsruhe Institute of Technology (KIT)
Max Planck Institute (MPI)
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Cyprus Institute

European Commission Joint Research Centre
Institute for Environment and Sustainability, Joint Research Center
Istituto Nazionale di Ottica

Academy of Athens
Aristotle University of Thessaloniki

Finnish Meteorological Institute
University of Helsinki

China Meteorological Administration
Collaborative Innovation Center for Regional Environmental Quality
Chinese Academy of Meteorological Sciences
Hong Kong Polytechnic University
Chinese Academy of Sciences
Ministry of Education
Nanjing University
Nanjing Institute of Meteorology
Peking University
Tsinghua University
University of Chinese Academy of Sciences
University of Science and Technology China

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Kasetsart University

Aryabhatta Research Institute of Observational Sciences
Dayalbagh Educational Institute
Indian Institute of Remote Sensing
Indian Institute of Technology
Indian Institute of Tropical Meteorology
National Physical Laboratory India
National Remote Sensing Centre – Indian Space Research Organization
Physical Research Laboratory India
Vikram Sarabhai Space Centre

A.M. Obukhov Institute of Atmospheric Physics of Russian Academy of Sciences

7

Chungnam National University
Gwangju Institute of Science and Technology (GIST)
Korea Aerospace Research Institute
Pusan National University
Seoul National University
Yonsei University

Asia Center for Air Pollution Research (ACAP)
Hokkaido University
Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
Japan Meteorological Agency
Kyushu University
Meteorological Research Institute
Nagoya University
National Institute for Environmental Studies of Japan (NIES)

5

Commonwealth Scientific and Industrial Research Organization (CSIRO)
University of Wollongong

National Institute of Water and Atmospheric Research (NIWA)

1

TOTAL OF
511
INSTITUTIONS

FROM
57
COUNTRIES

SOURCE ► Web of Science, Scopus

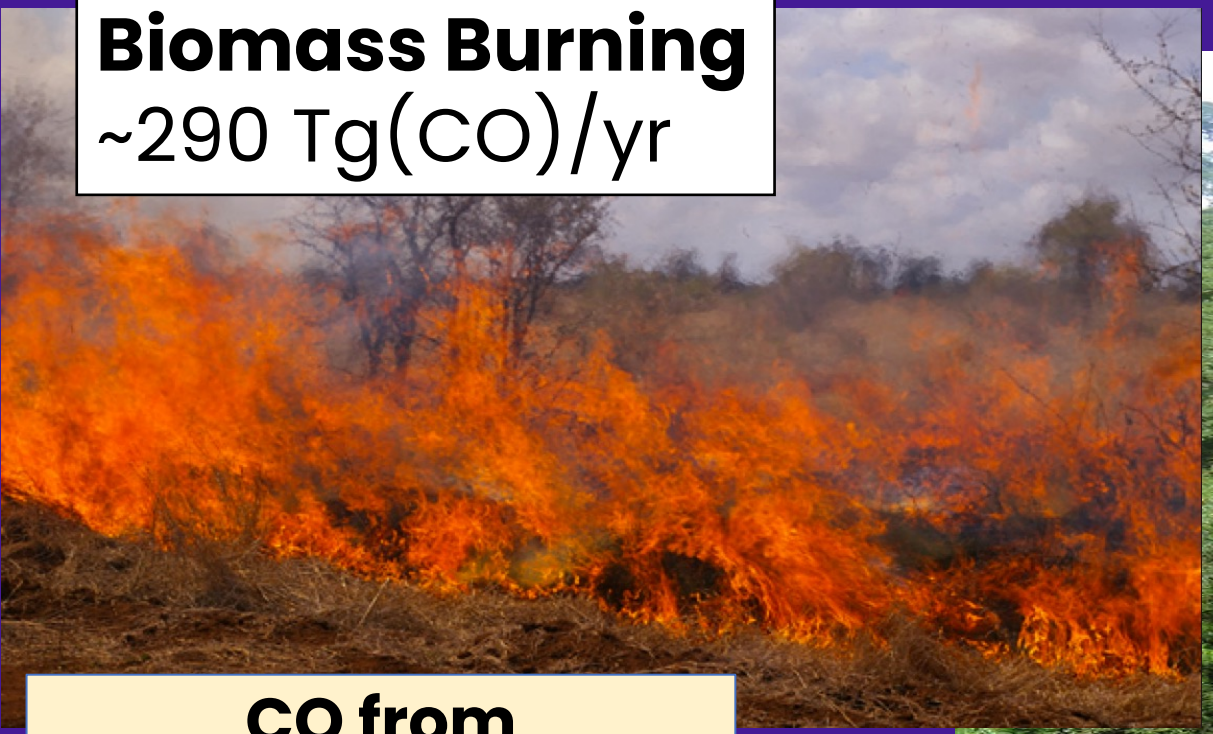
Worldwide data users have been identified from the list of affiliations associated with all MOPITT peer-reviewed publications.
Only countries with institutions whose publication count is greater than two are shown.
Only institutions whose publication count is greater than two are listed.
For the United States, only institutions whose publication count is greater than four are listed.

MOPITT ON TERRA

Carbon monoxide emissions

Main surface sources of CO

Biomass Burning
~290 Tg(CO)/yr



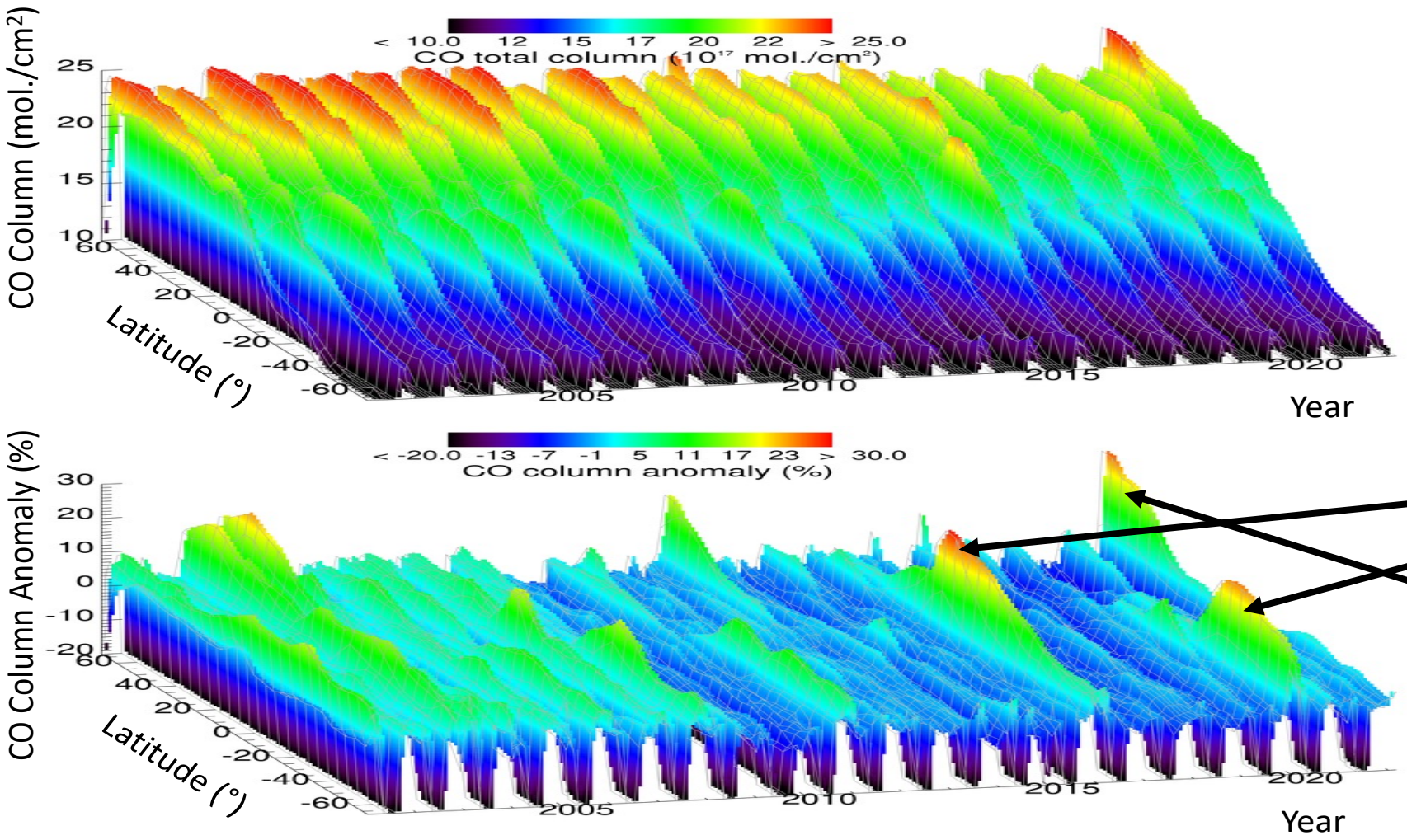
CO from methane oxidation:
~850 Tg(CO)/yr

Fossil Fuel Combustion
~535 Tg(CO)/yr

Biogenic NMVOC oxidation
~566 Tg(CO)/yr

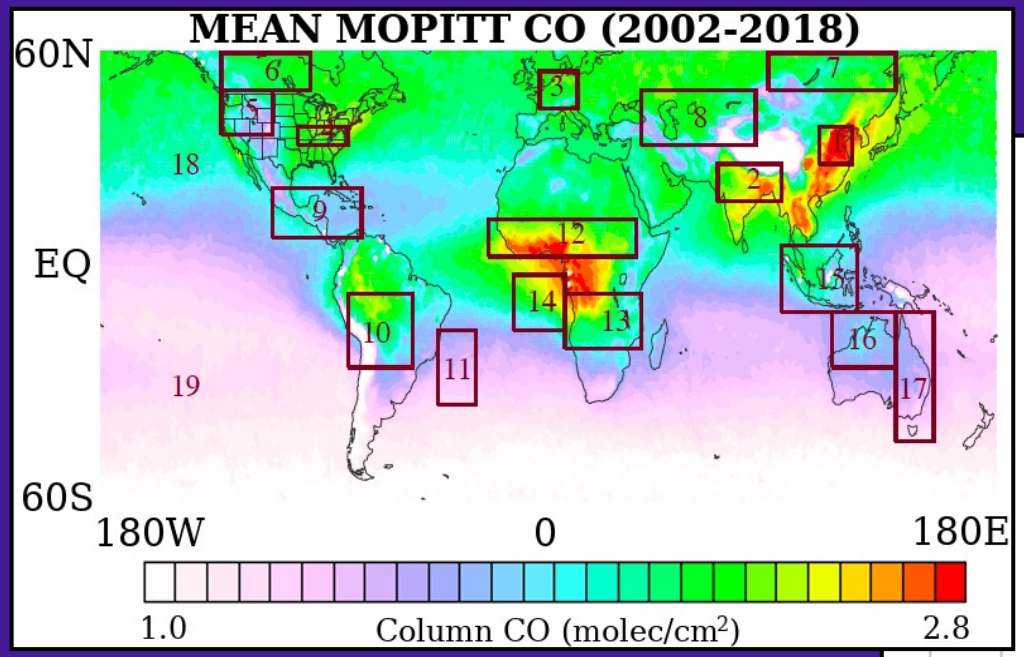
2005-2012 averages
from Worden et al., ACP, 2019

MOPITT data record of global CO observations



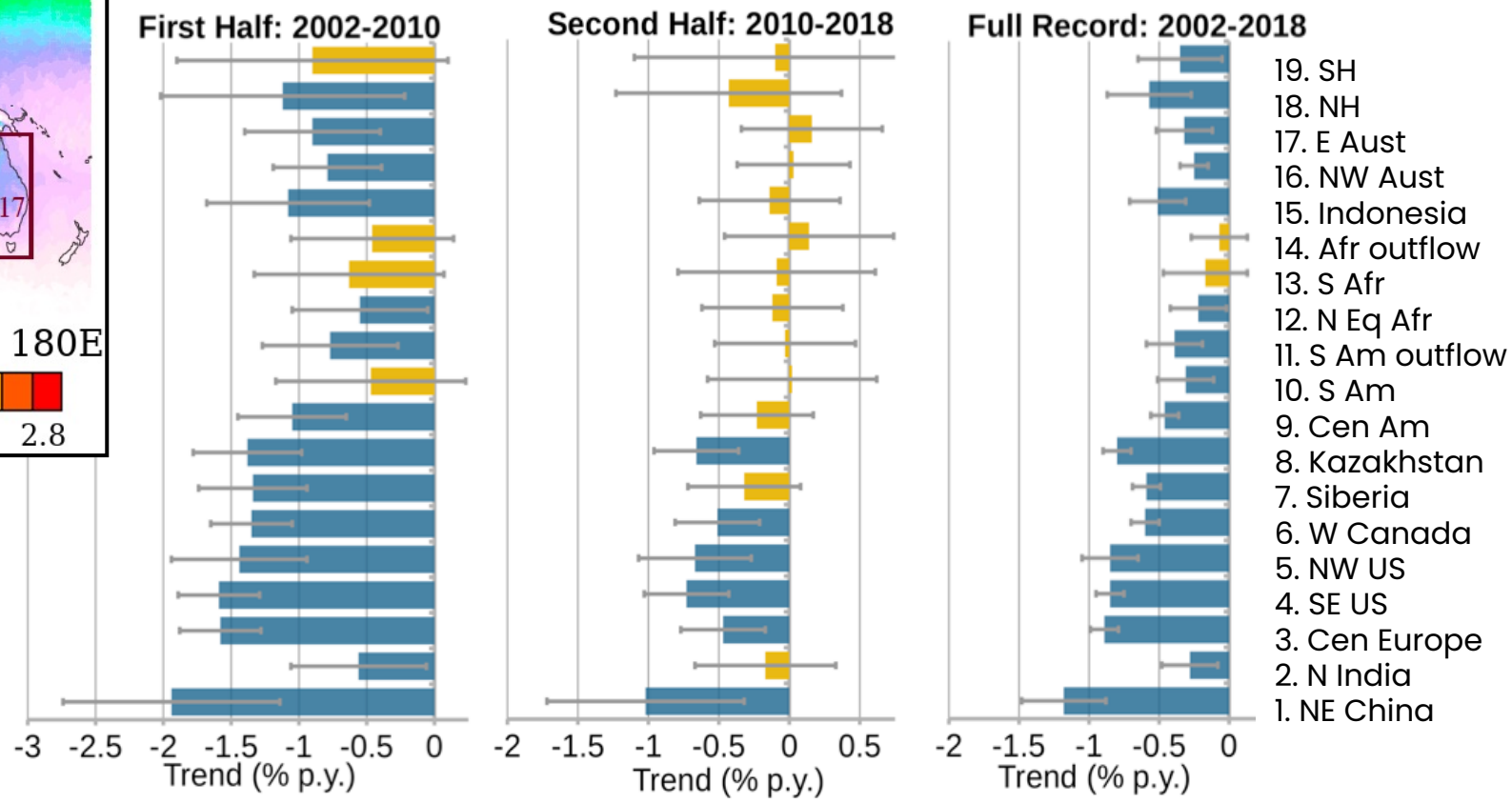
Atmospheric CO is mostly decreasing due to combustion efficiency improvements in technology and overall decreases in tropical burning, but extreme fires in Indonesia during the 2016 El Nino, in Australia 2019-20 and Siberia 2021 have produced the highest anomalies (%) over the MOPITT record.

Regional trends in carbon monoxide



Buchholz et al., RSE, 2021
(cited in IPCC AR6, Ch. 6)

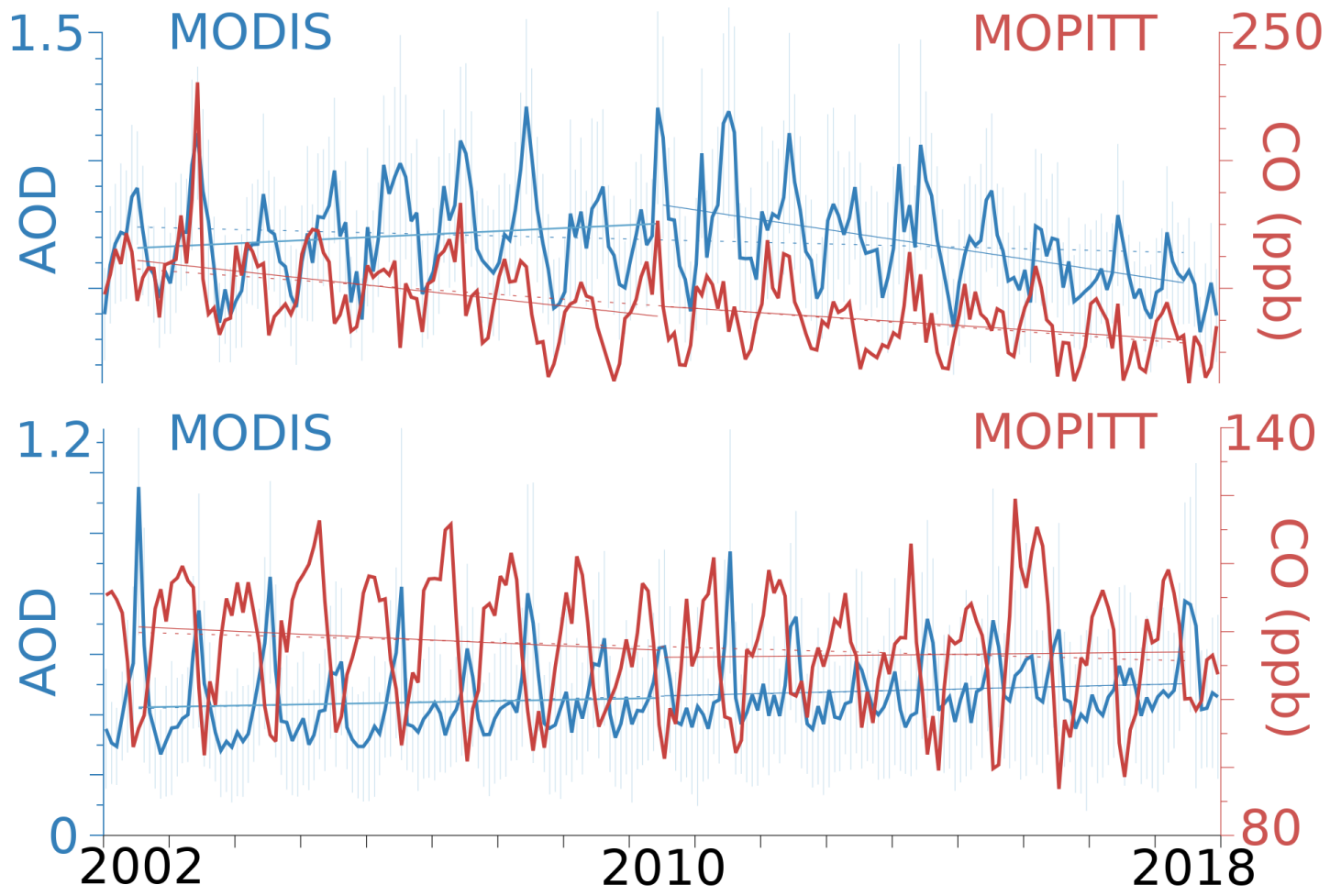
Regional trends using
MOPITT V8T data



Trend significant > 1σ

Less significant <1σ

Trends in Asian CO and Aerosol Optical Depth (AOD)

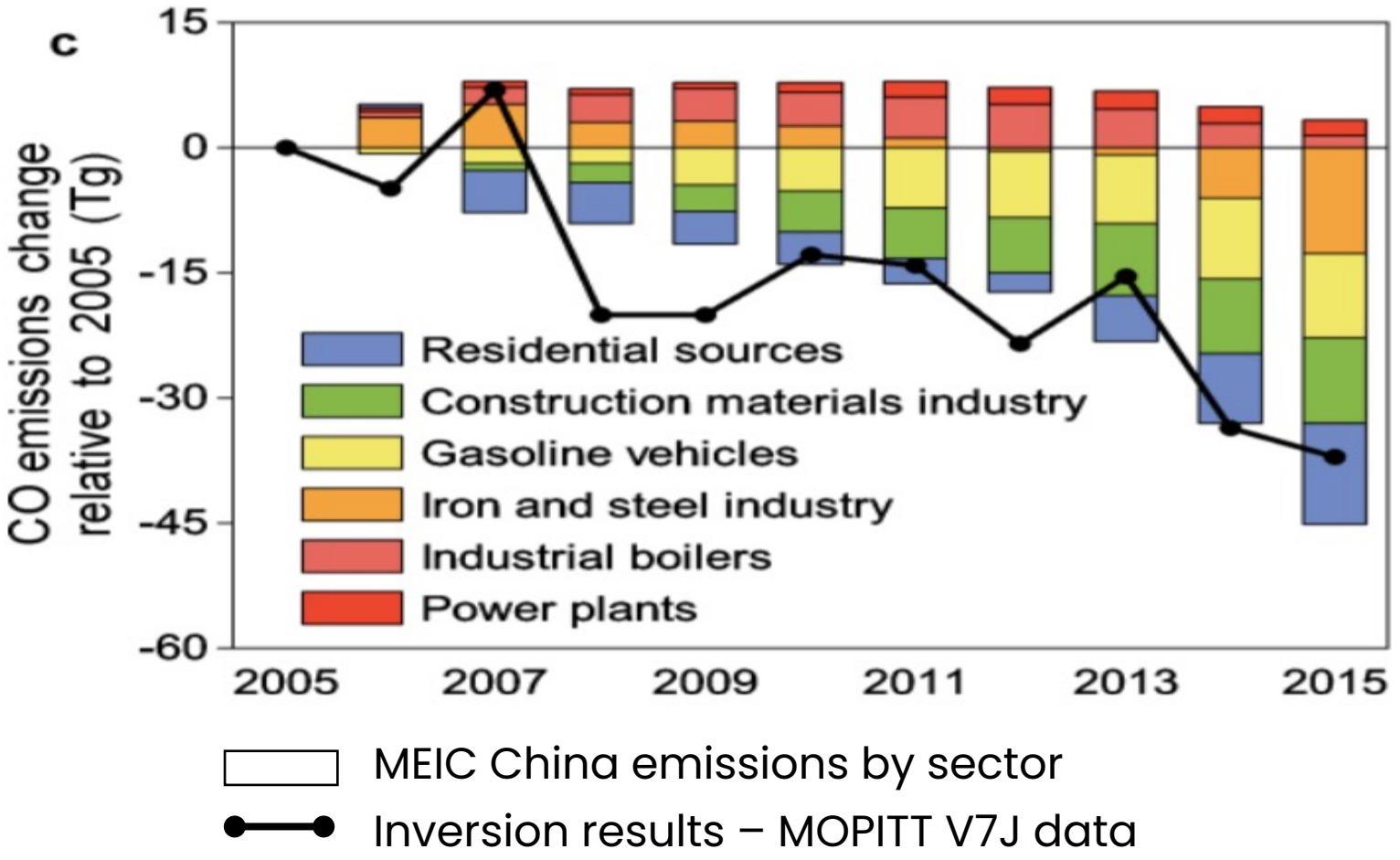


Northeast China:
AOD inflection at ~2010 following enactment of clean air policies.

Northern India:
Increasing AOD and local CO emissions cancel out global CO decrease.

Buchholz et al., RSE, 2021

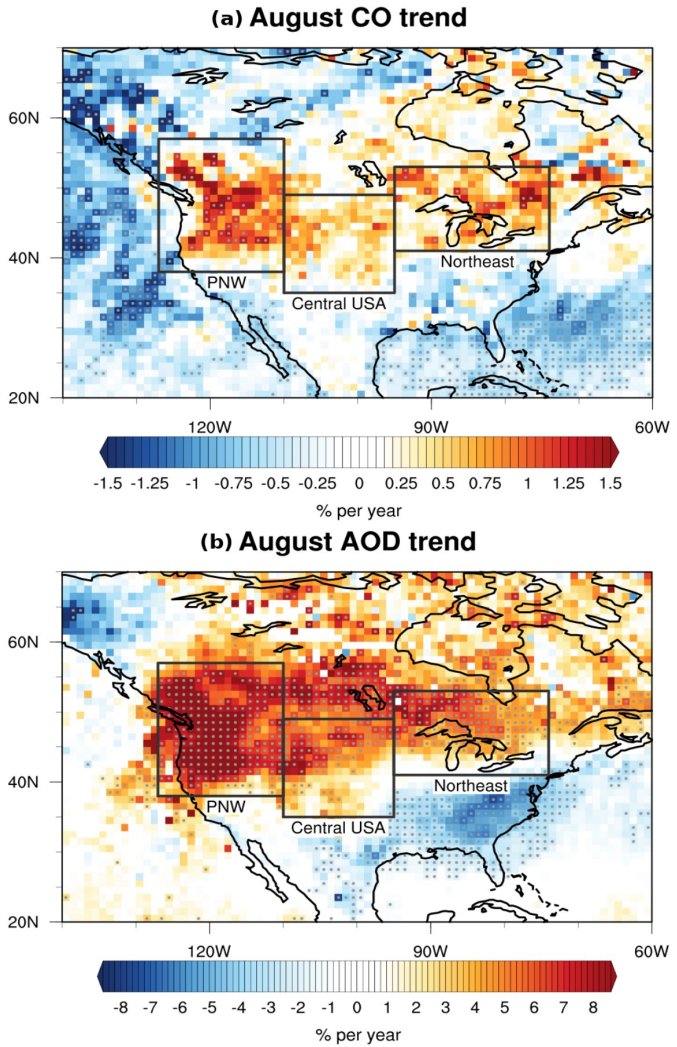
Changes in Chinese CO emissions

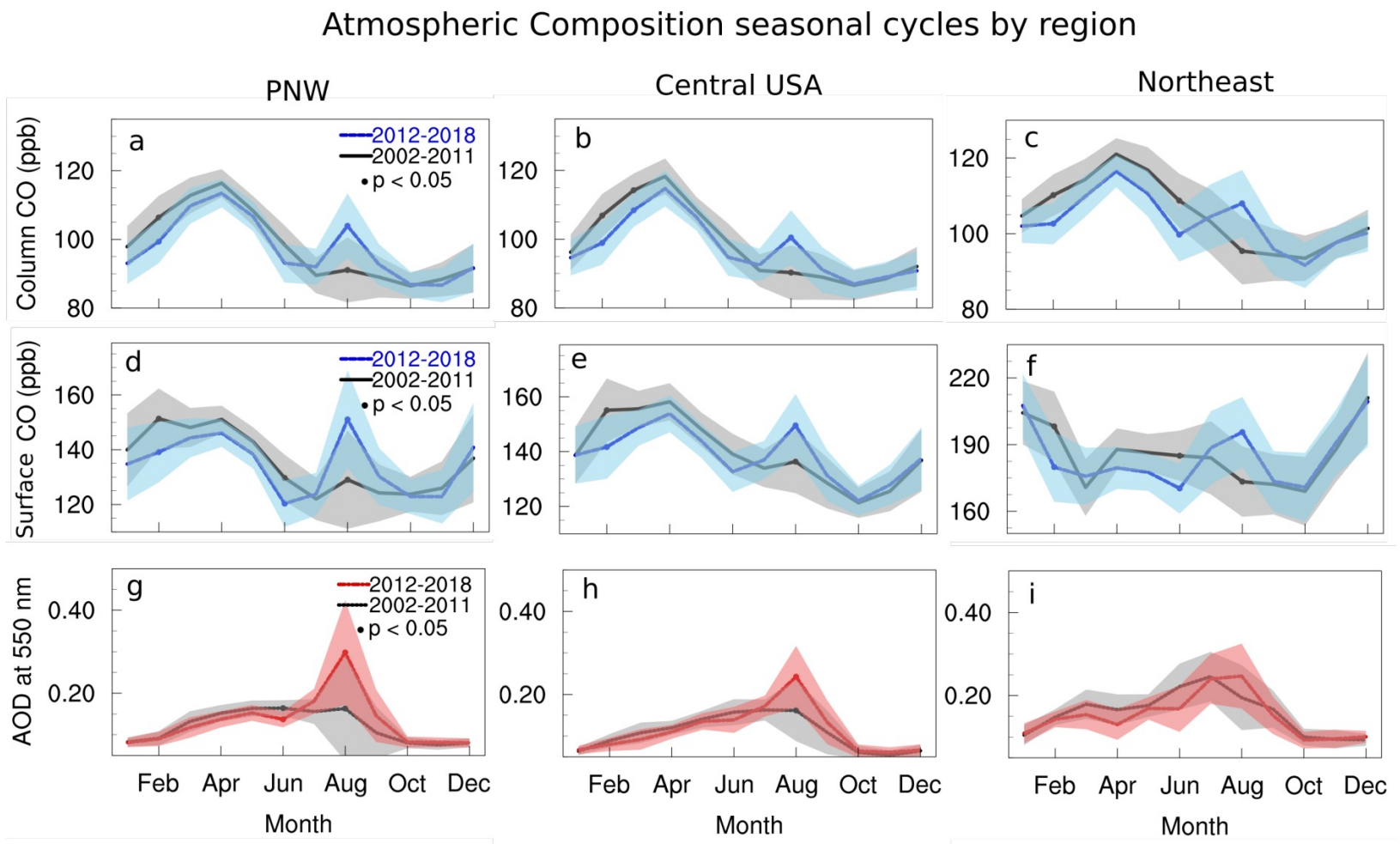


- Good agreement in MEIC bottom-up and top-down CO emission trends.
- Largest reductions are in the iron/steel industry and residential sectors

Zheng et al., ERL, 2018

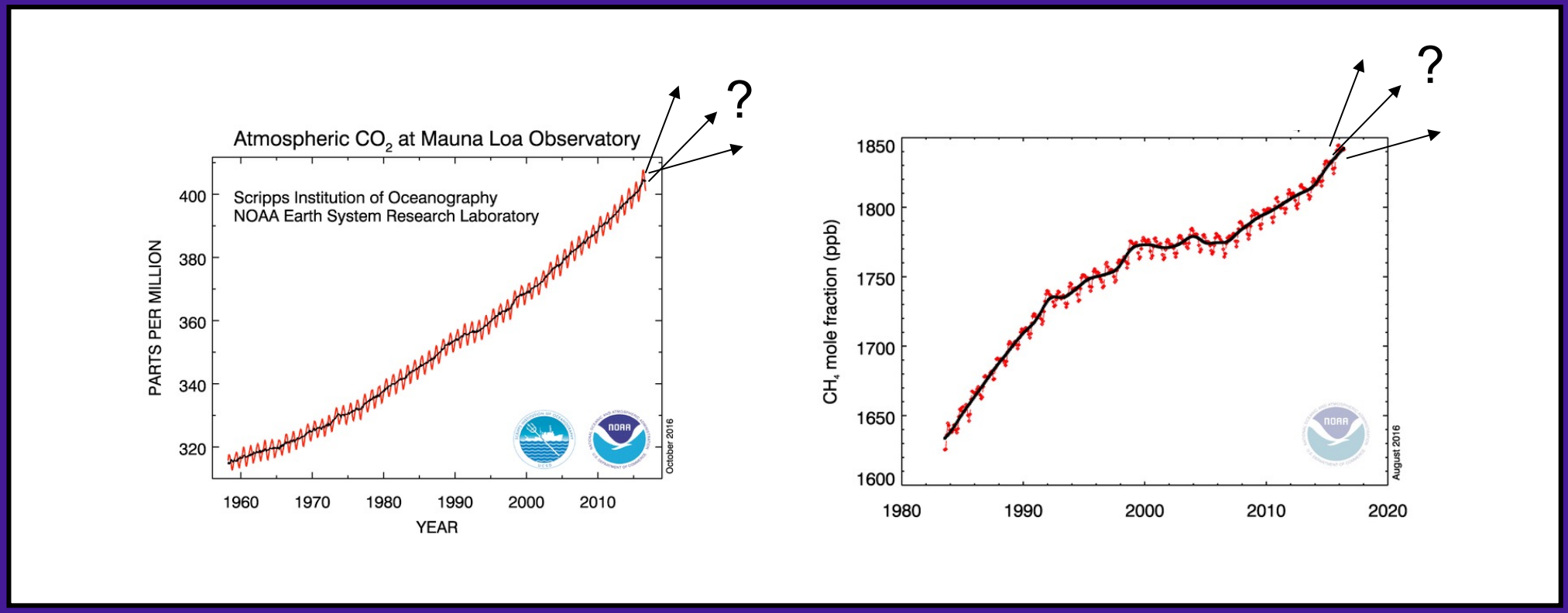
Increase in western fires has changed the seasonal pattern in CO and AOD





Buchholz et al., *Nature Comm.*, 2022

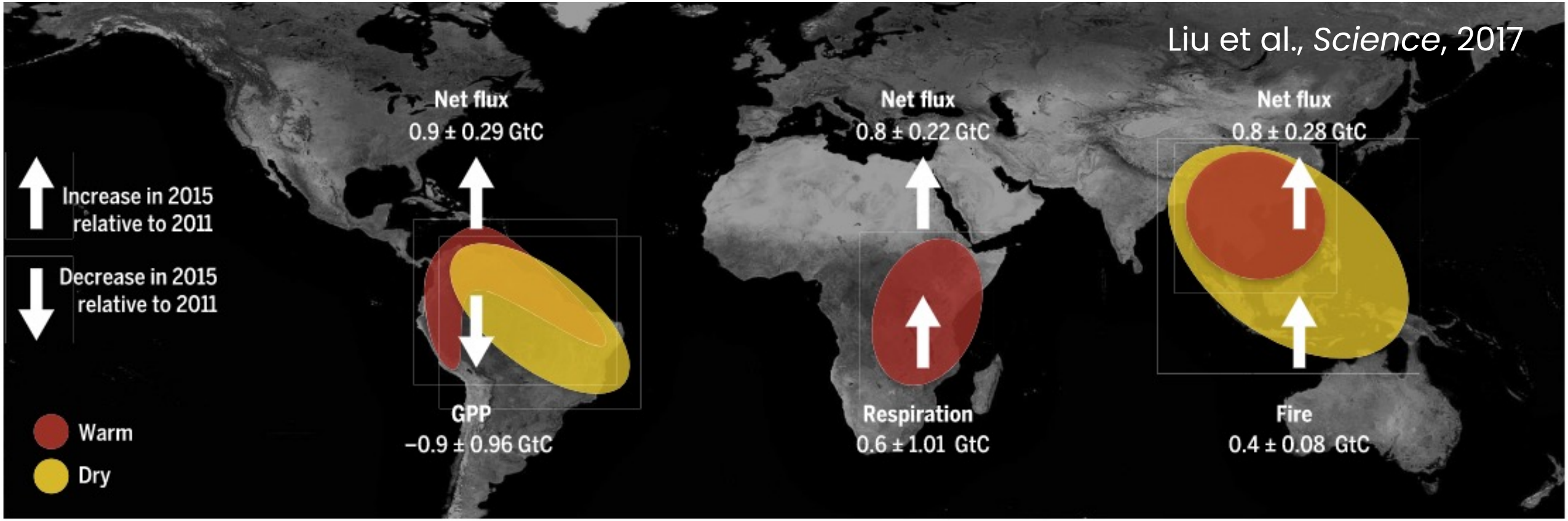
What are the future atmospheric concentrations and their growth rate of the two most important green house gases?



Growth rate of CO_2 and CH_4 depend on emissions as well as feedbacks and interactions between climate and the energy, carbon, and water cycles.

CO and CO_2

Carbon cycle science with OCO-2 CO_2, GOSAT SIF and MOPITT CO



Relative to 2011 La Niña, 2015 El Niño released 2.5 ± .34 GtC more carbon

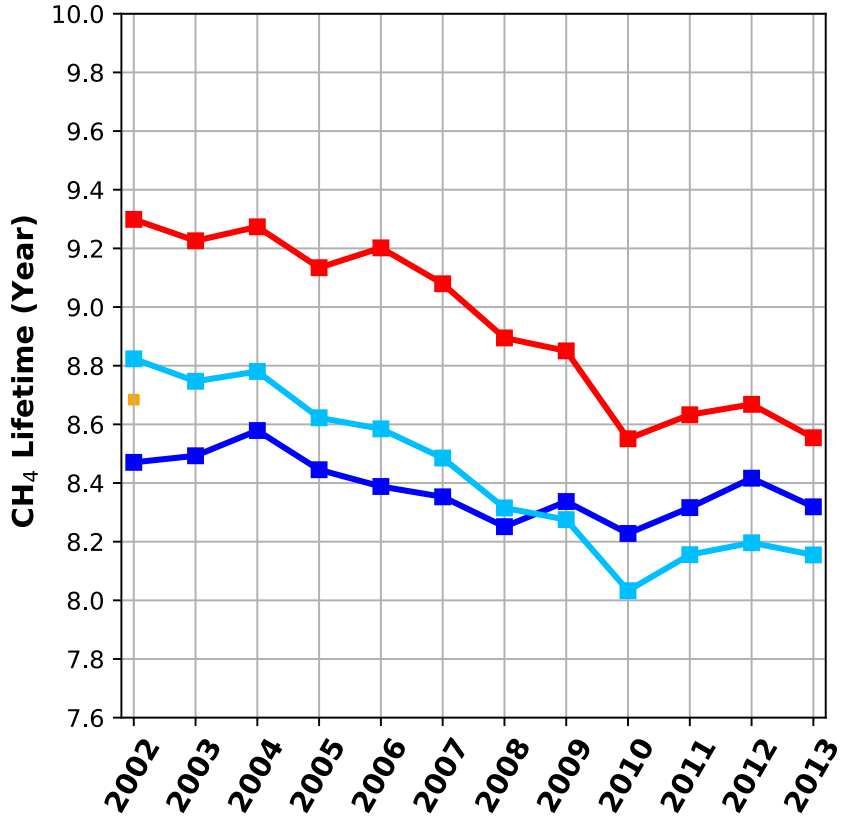
CH_4 Chemical response from CO changes over time

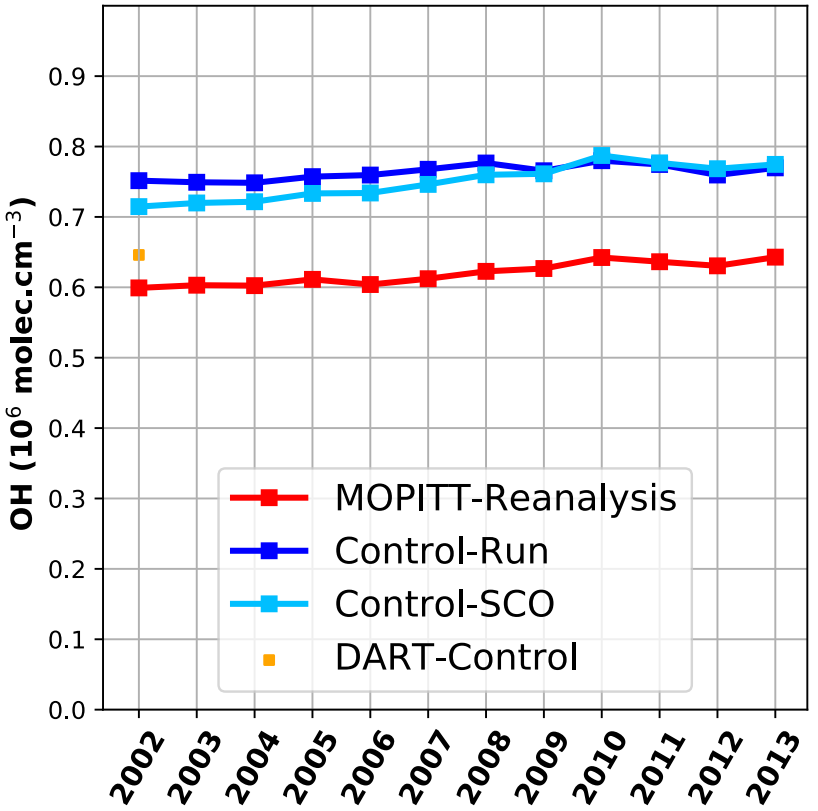
1) **Decrease in CO; Decrease in CO +OH reaction;**

2) **Decrease in CH_4 lifetime / increase in OH**

8% (9 months) decrease in methane lifetime

11 Years





The shorter CH_4 lifetime is not due to a change in meteorology

Gaubert et al., *GRL*, 2017

Impacts of Terra Orbit Changes

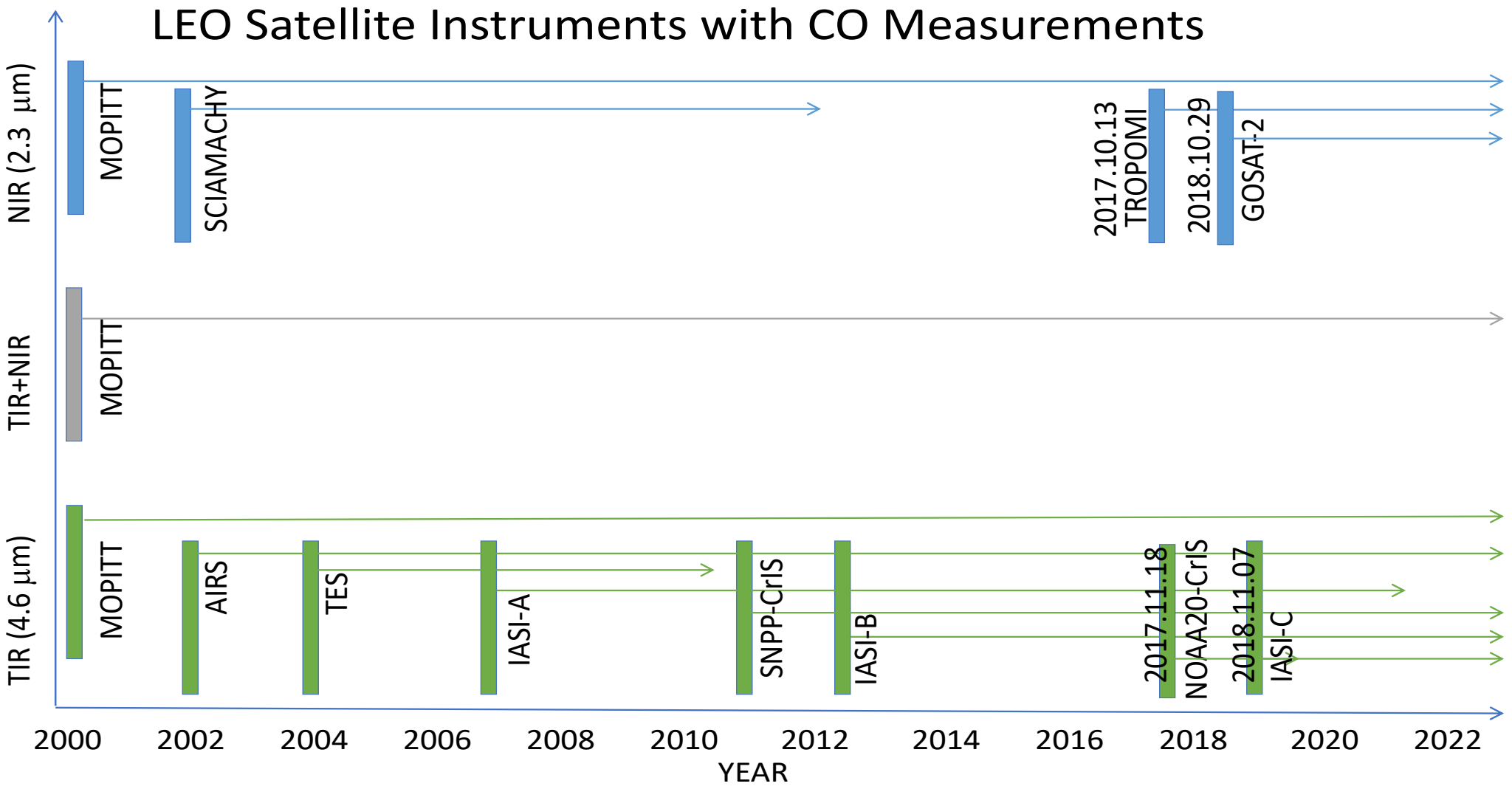
- Largest impact is to the MOPITT surface sampling pattern:
  - Will no longer be repeating every 16 days (but still close to repeat)
  - However, sample locations will be reported with the data in the same format as current data (i.e., data assimilation is not affected)

- MOPITT single pixel footprint size will decrease slightly, by 1.6%, as the orbit altitude is lowered from 705 km to 694 km.

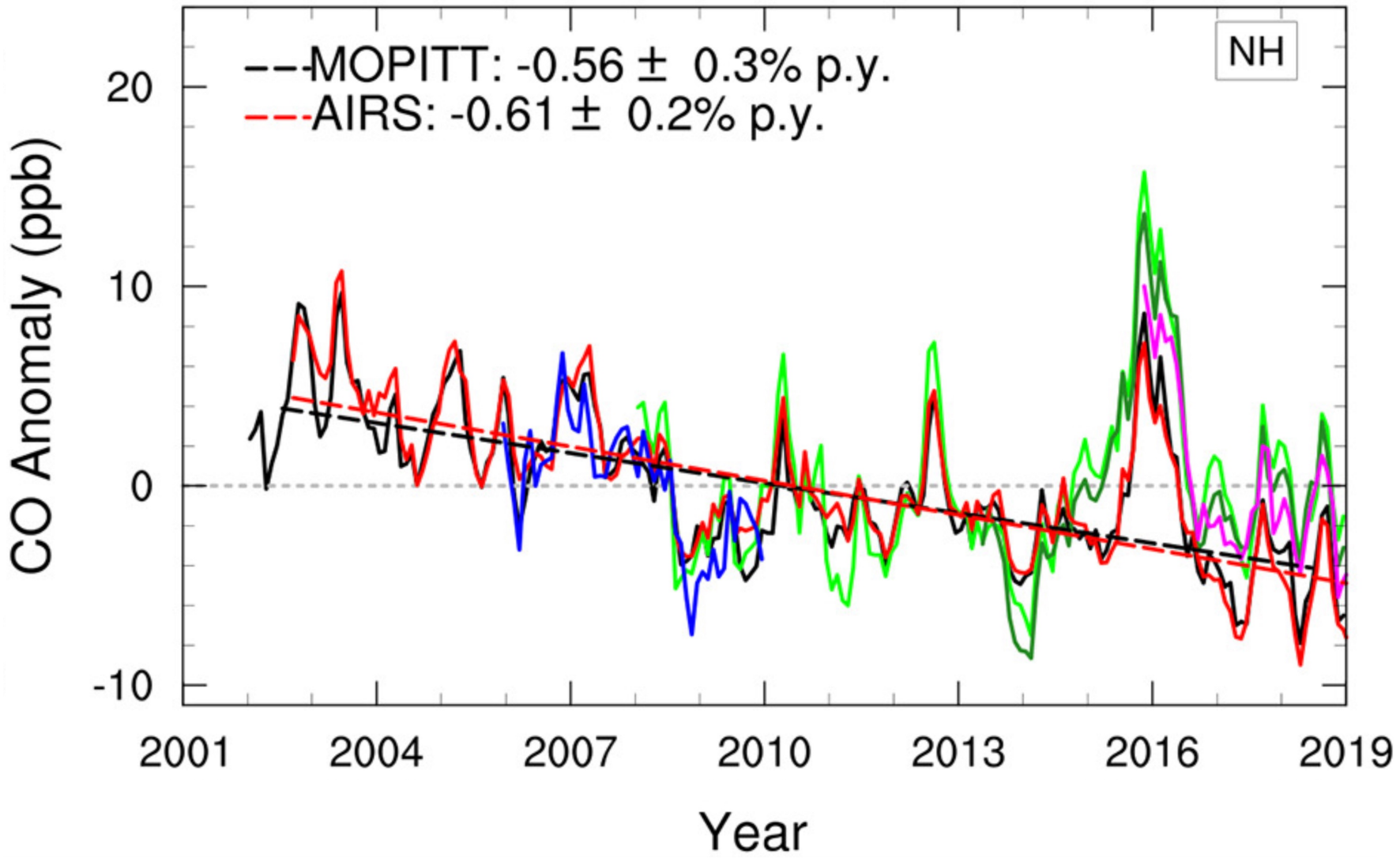
- We do not expect significant impacts to MOPITT retrieval quality.
  - The TIR product is independent of the sun angle and so is mostly unaffected
  - The NIR product will have minimal changes because of the crossing time/sun
  - The geo-registration will reported in the same way

- Terra Constellation Exit Maneuver (CEM) completed 19 Oct. 2022
- MOPITT is back online after post-CEM calibration

Continuity of CO measurement



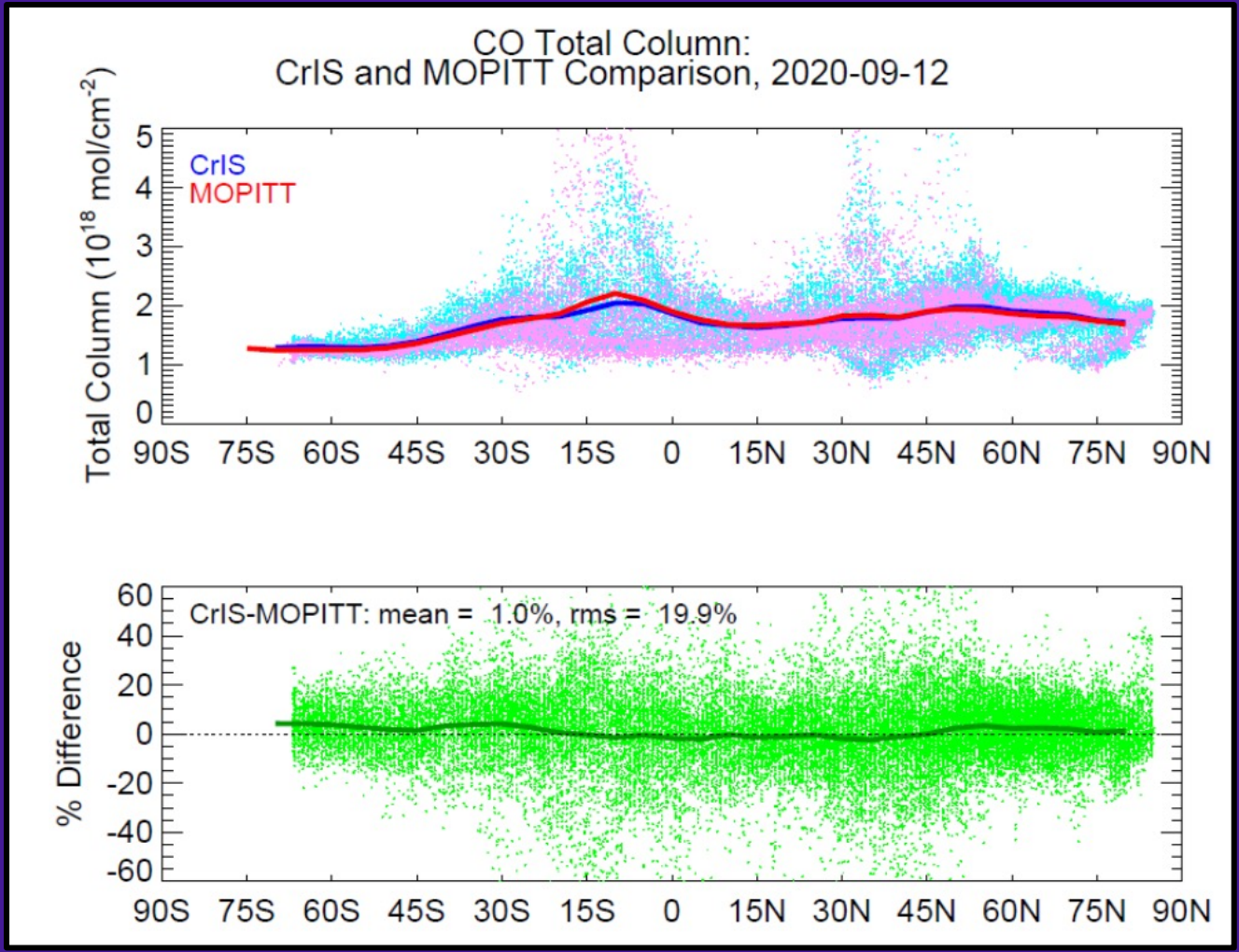
Continuity of CO measurements

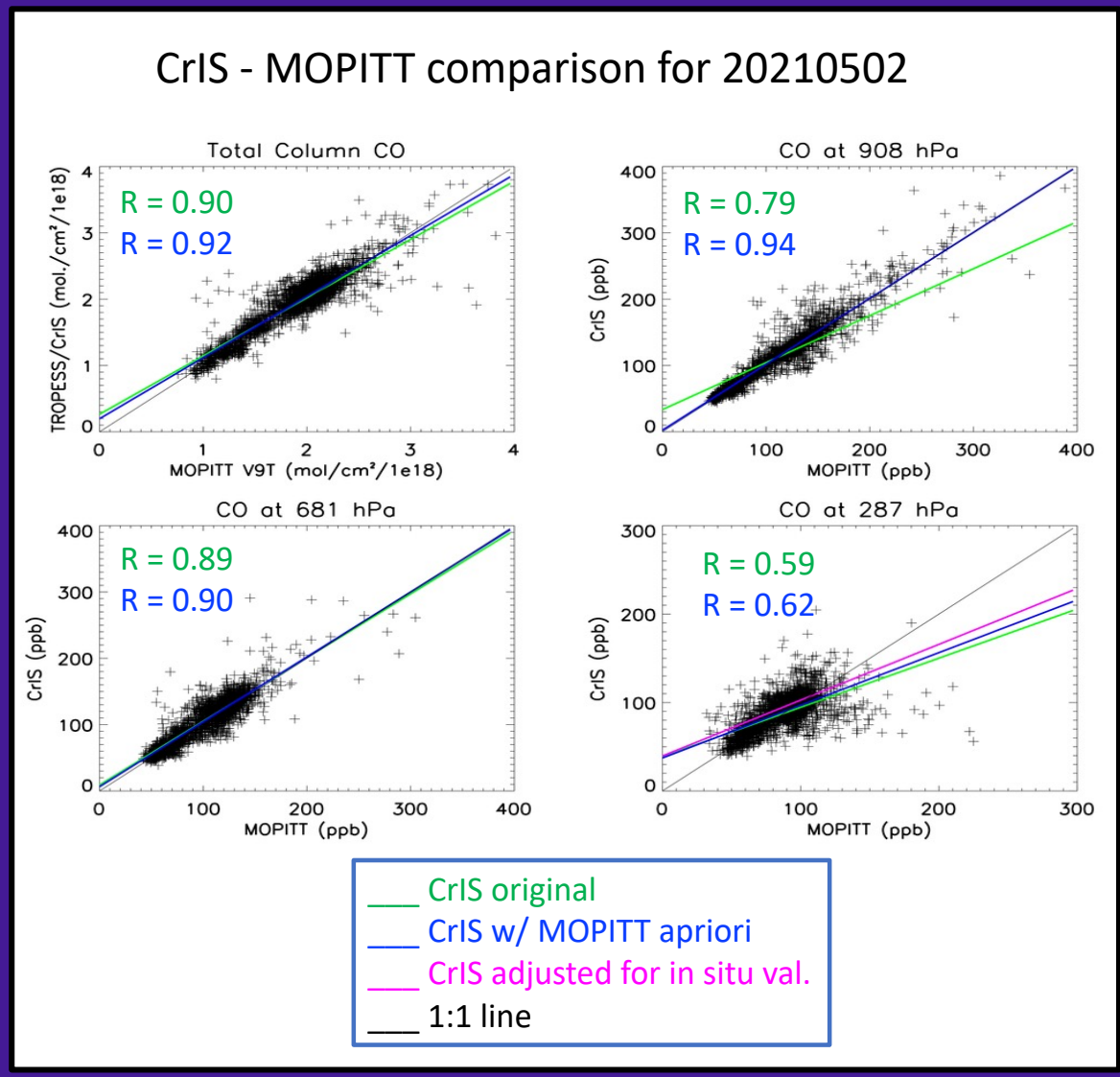


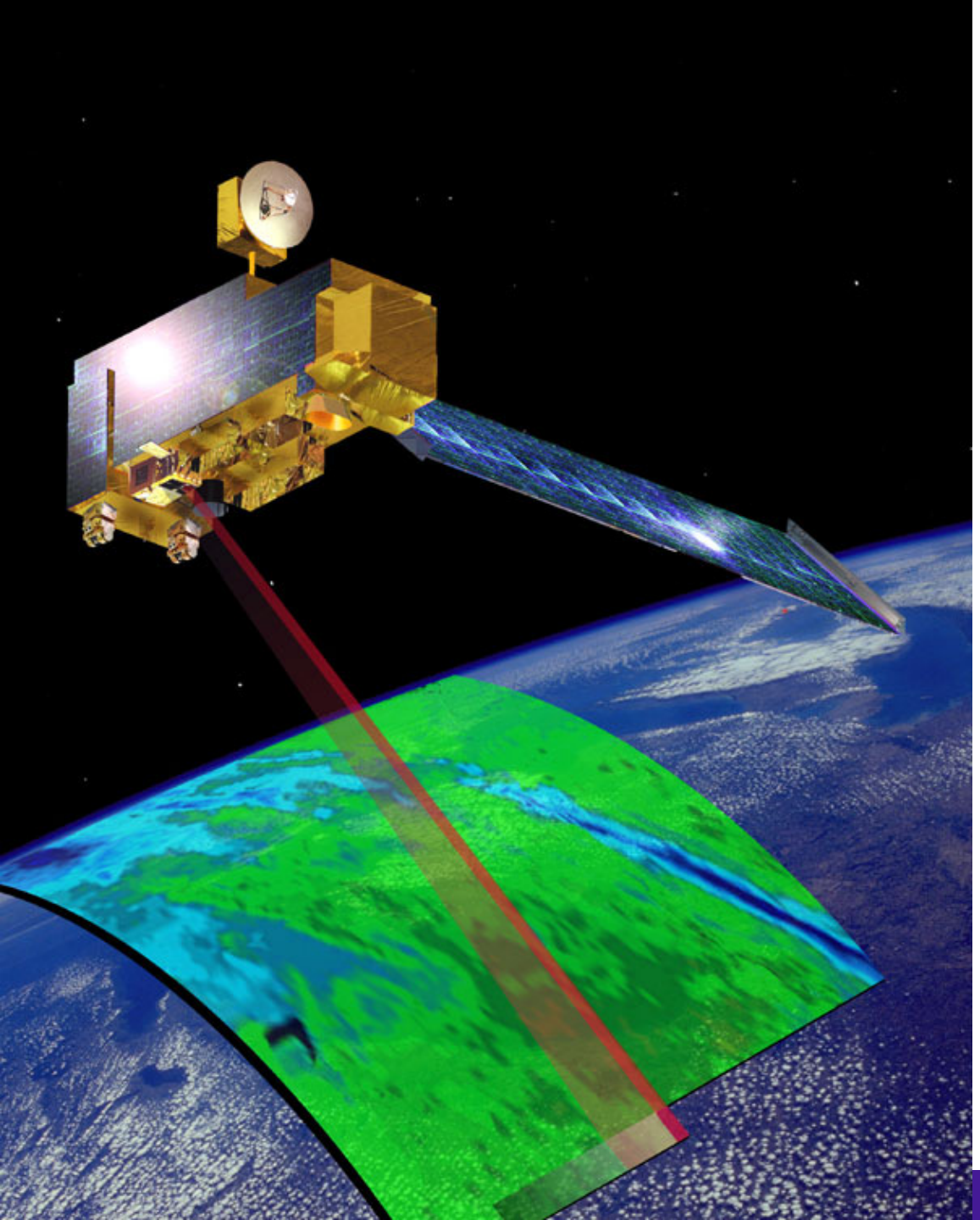
- Total Column CO from all satellite TIR observations
- All observe the same seasonality
- Some records not long enough for trends, but all have consistent anomalies

Buchholz et al., *RSE*, 2021

Continuity of CO measurements: CrIS vs. MOPITT comparisons







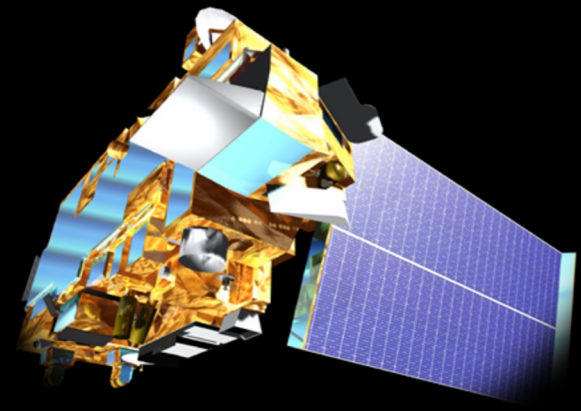
MOPITT Summary

- MOPITT has a unique record of multispectral CO observations, used for air quality forecasts, emission estimates and trends, attribution of co-emitted GHG and understanding atmospheric chemistry

- No significant differences in retrieval quality are expected from orbital changes. ECMWF has not found anomalies post-CEM and continues to assimilate MOPITT data.

- MOPITT team is using CrIS CO (TIR-only) observations to extend the TIR MOPITT record and investigating CrIS+TROPOMI (SWIR-only) retrievals to extend the multispectral record.

Thank you!



and thanks to **NASA**, **CSA**, **U. Toronto** and the **NCAR MOPITT team**:

R. Buchholz, M. Deeter, D. Edwards, L. Emmons, G. Francis, J. Gille, B. Gaubert, D. Mao, S. Martinez-Alonso, I. Ortega, G. Pfister, W. Tang, D. Ziskin

NCAR

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Miguel Román, GSFC

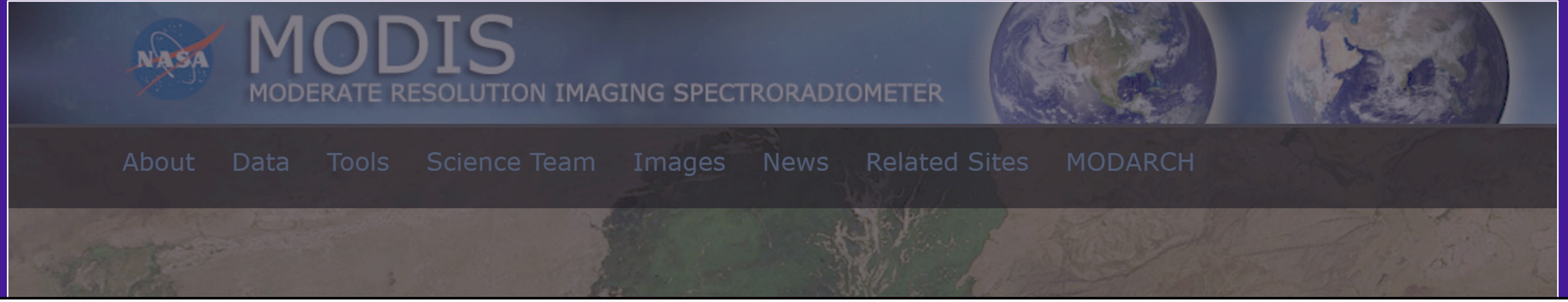
Follow @NASA_MODIS

Inland Niger Delta at the End of the Rainy Season

On October 31, 2022, the Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASA's Aqua satellite acquired a true-color image of central Mali, showing the Inland Niger Delta wetlands flush with vegetation after a long and wet rainy season...

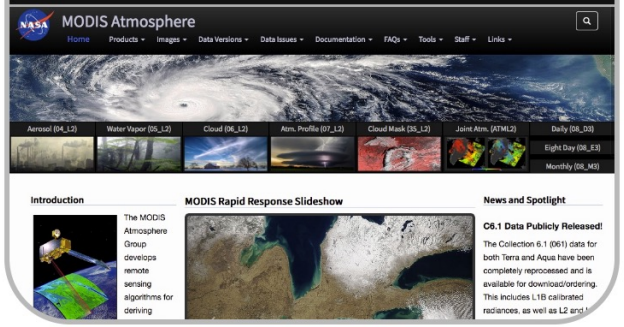
Continue Reading

Data	News	Tools
The MODIS Data section contains everything from ATBDs to Product	Terra Data and Imagery Outage Starting October 10	The MODIS Tools section has a complete listing of web-based tools

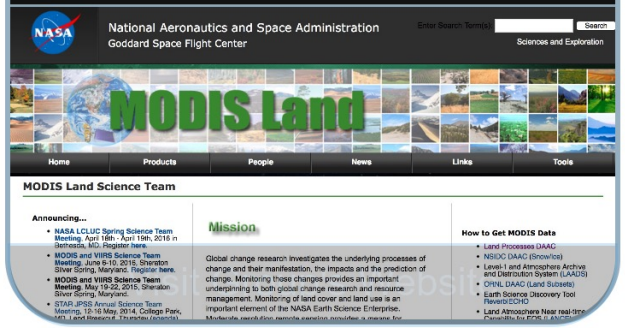


Disciplinary Teams

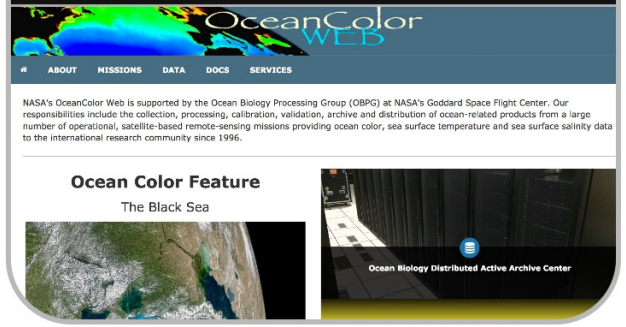
Atmosphere



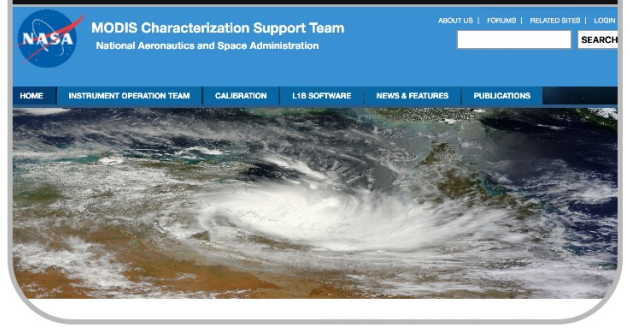
Land



Ocean



Calibration



Data

The MODIS Data section contains everything from ATBDs to Product

News

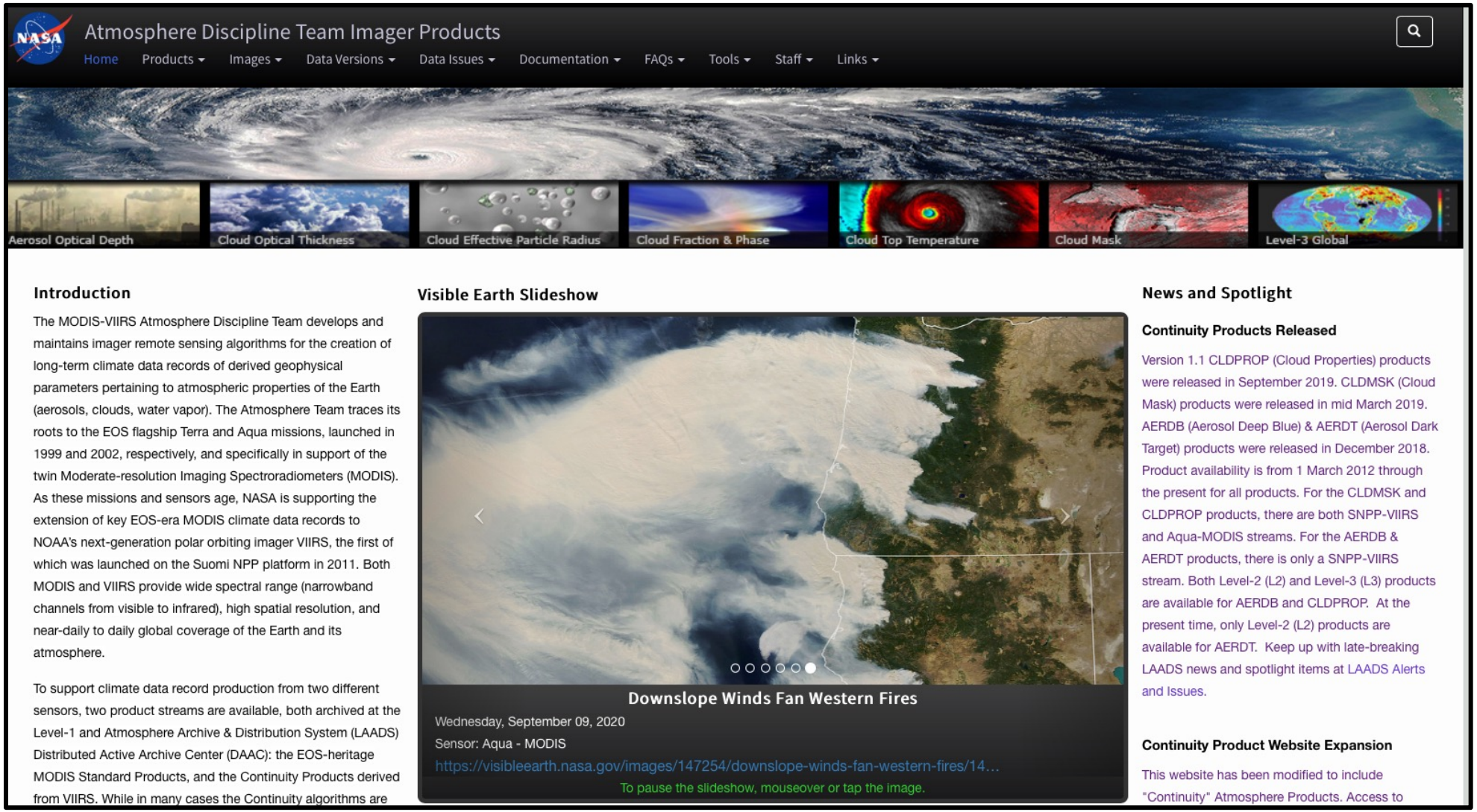
Terra Data and Imagery Outage Starting October 10

Tools

The MODIS Tools section has a complete listing of web-based tools

MODIS Atmosphere Team

atmosphere-imager.gsfc.nasa.gov or search on ***MODIS + Atmosphere***



MODIS Atmosphere Team: Principal Products

Aerosol Level-2

- Dark Target (*Levy*), Deep Blue (*Hsu*) algorithms
- Optical depth, etc.
- 10km, 3km

Cloud Level-2

- Cloud mask (1km, with 250/500m info.): *Holz, Ackerman*
- Cloud properties
  - Cloud Top: Pressure, Temp., Height (5km, 1km): *Holz, Menzel*
  - Optical/Microphysical: Phase, Optical Thickness, Particle Effective Radius, derived Water Path, uncertainties, etc. (1km, with partly cloudy filtering, sub-pixel heterogeneity info.): *Platnick, Meyer*

Clear Sky Level-2

- Profiles/TPW: IR-based (5km) (*Borbas, Menzel, Ackerman*)

Temporal/Spatial Statistics Level-3

(*Platnick, Meyer, Holz*)

- Aerosol, cloud, clear sky: hundreds of scalar and histogram datasets
- 1° equal angle grid; daily, 8-day, monthly
- MODIS Terra and Aqua separately
- Special L3 products: COSP (combined Terra & Aqua), GEWEX

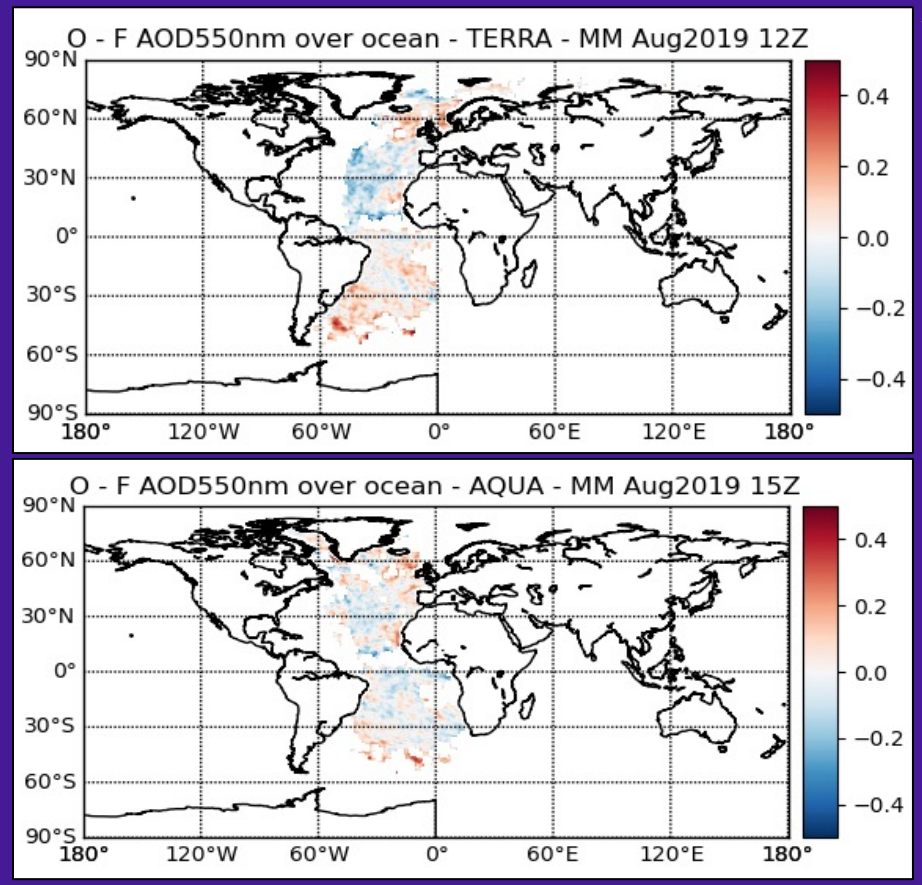
MODIS Atmosphere Team: Additional Context

- All L2 algorithms rely on absolute radiometric calibration
- All products in Collection 6.1 production (2017/18); teams working on Collection 7 (Senior Review maintenance funding)
- All teams also works on SNPP/JPSS continuity products in production since late 2018 to early 2020); aerosol and cloud teams working on GEO algorithms (ROSES MEaSUREs, ESROGSS).

Importance of Terra for Aerosol Data Assimilation

- Aerosol data assimilation is now practiced in several centers worldwide.
- MODIS, with its AM (Terra) and PM (Aqua) overpasses, continues to be the main data source for global aerosol data assimilation.
- Forecast errors are larger in the morning when data was last seen in the afternoon of the previous day
- Forecasts errors tend to be smaller in the afternoon since data has typically been assimilated in the morning due to the availability of Terra data.

Virginie Buchard & Arlindo da Silva, NASA/GSFC



Monthly mean observation minus forecast residual in the morning (Terra) and in the afternoon (Aqua).

Assimilation of Terra measurements in the morning reduces the forecast errors in the afternoon.

Terra/MODIS Aerosol Products: Potential approaches

- **Enable reduced uncertainties: Radiometric Continuity**

  Overlap with CLARREO Pathfinder, *Yolanda Shea (LaRC)*

- **Enable reduced uncertainties: Exploiting Local Time distributions**

  Exploiting local time distributions to understand MODIS cloud retrieval sensitivity to pixel size view/solar geometry, *Kerry Meyer (GSFC)*

- **Enabling Unique Data Record and Continuity Overlap**

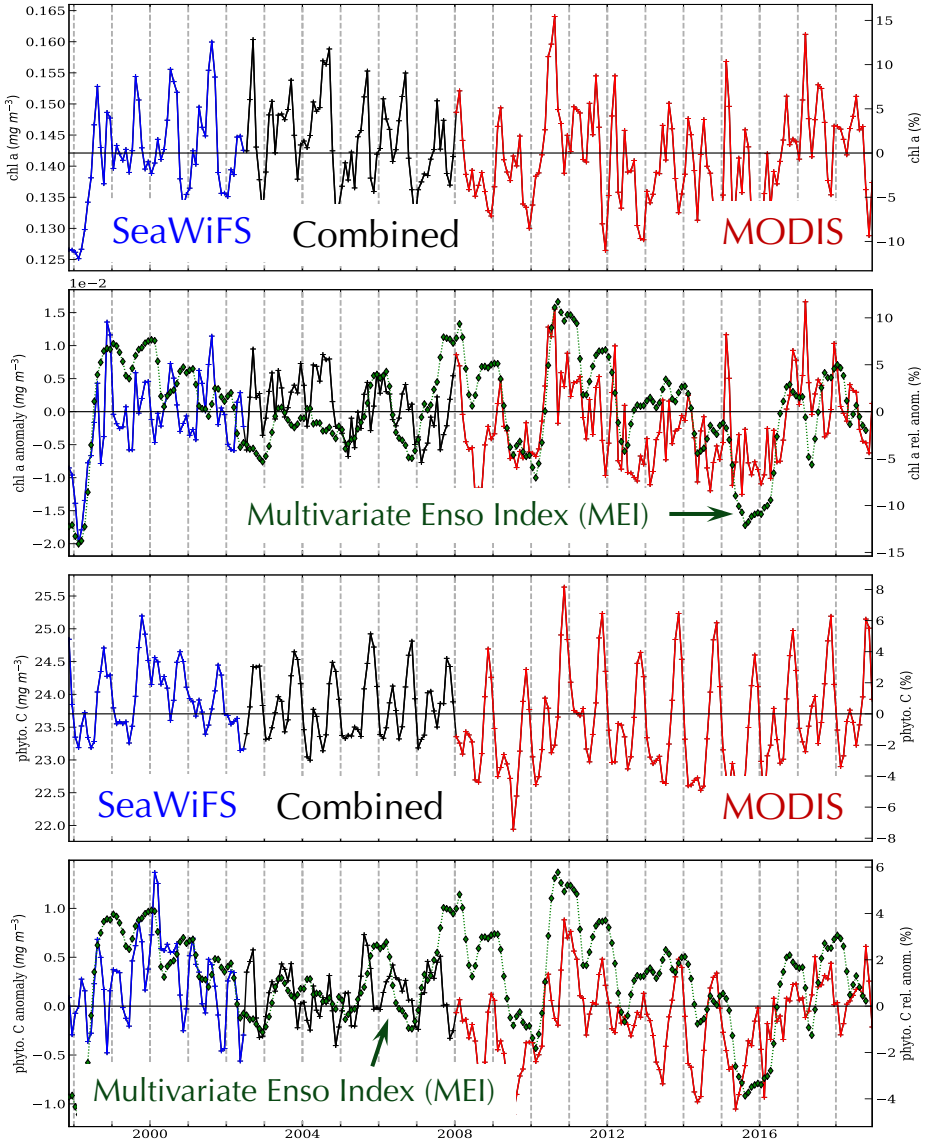
  Science and applications for clouds and aerosols supported by the continuation of the morning Terra orbit, *Bob Holz (U. Wisc., Madison)*

Terra/MODIS Ocean Products

- Sea Surface Temperature
- Remote Sensing Reflectance
- Chlorophyll-a Concentration
- Diffuse Attenuation at 490 nm
- Particulate Organic Carbon
- Particulate Inorganic Carbon
- Normalized Fluorescence Line Height (FLH)
- Instantaneous Photosynthetically Available Radiation
- Daily Mean Photosynthetically Available Radiation

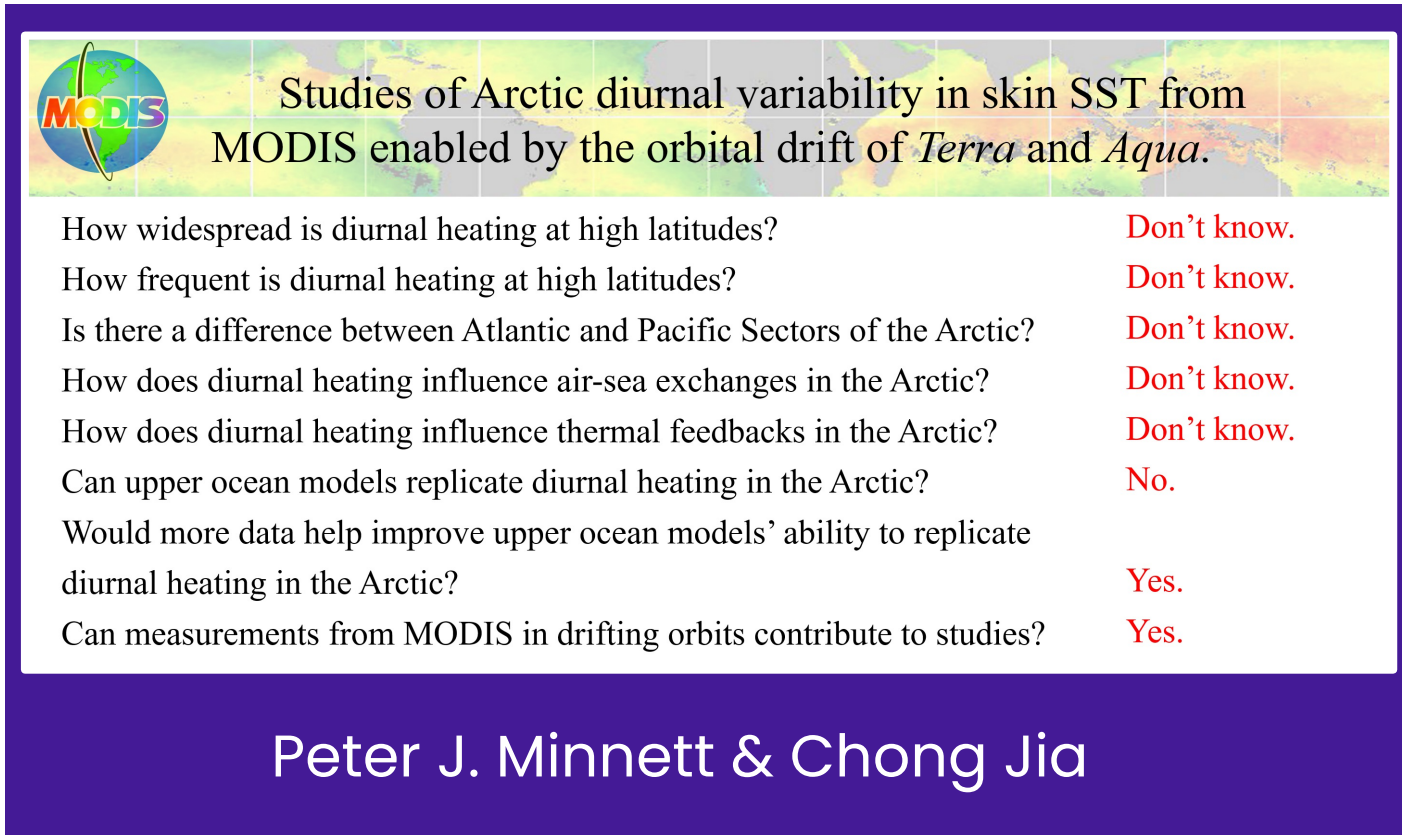
Maintaining the Ocean Color Climate Data Record

- MODIS has enabled establishment of a long-term (22+ year), consistent data record of the ocean's biological response to major climatic events.
- Global mean mid-latitude (+/- 40) chlorophyll concentration and deseasonalized anomaly.
- Global mean mid-latitude (+/- 40) phytoplankton carbon concentration and deseasonalized anomaly.



MODIS Oceans Discipline: Diurnal Heating

- The drifting orbit period for MODIS can also uniquely enable studies of diurnal variability in sea surface temperature, as mean time of day for a given geographic region changes systematically from its 20-year reference.
- Failure to account for diurnal heating leads to significant errors in estimates of air-sea heat, momentum and gas exchanges and local heat and water budgets.
- The correct depiction of diurnal heating is also important for proper representation of air-sea exchanges of heat, moisture, and momentum in numerical weather prediction and climate models, and in air-sea exchanges of gases including CO2.
- Imaging radiometers on geostationary satellites provide good measurements to study diurnal heating at mid- and low-latitudes, **but not at high latitudes.**



MODIS Oceans Discipline

- Until the launch of PACE, MODIS on Aqua and Terra is the only ocean color sensor providing global measurements of phytoplankton chlorophyll fluorescence: a valuable indicator of phytoplankton physiology (see presentation by Lorraine Remer).
- Harmful algal blooms (HABs) are scientifically complex, economically damaging, and a threat to ecosystem and human health.
- **A gap between Aqua/Terra and PACE will threaten data continuity of these important systems.**

Terra/MODIS Land Products

- Surface Reflectance
- Land Surface Temperature
- Land Cover/Dynamics Products
- Vegetation Indices(NDVI & EVI)
- Thermal Anomalies/Fires
- Leaf Area Index (LAI) FPAR
- Evapotranspiration
- Gross Primary Productivity
- BRDF / Albedo / NBAR
- Vegetation Continuous Fields
- Water Mask
- Burned Area Product
- Water Reservoir

Terra/MODIS Land Products: Potential approaches

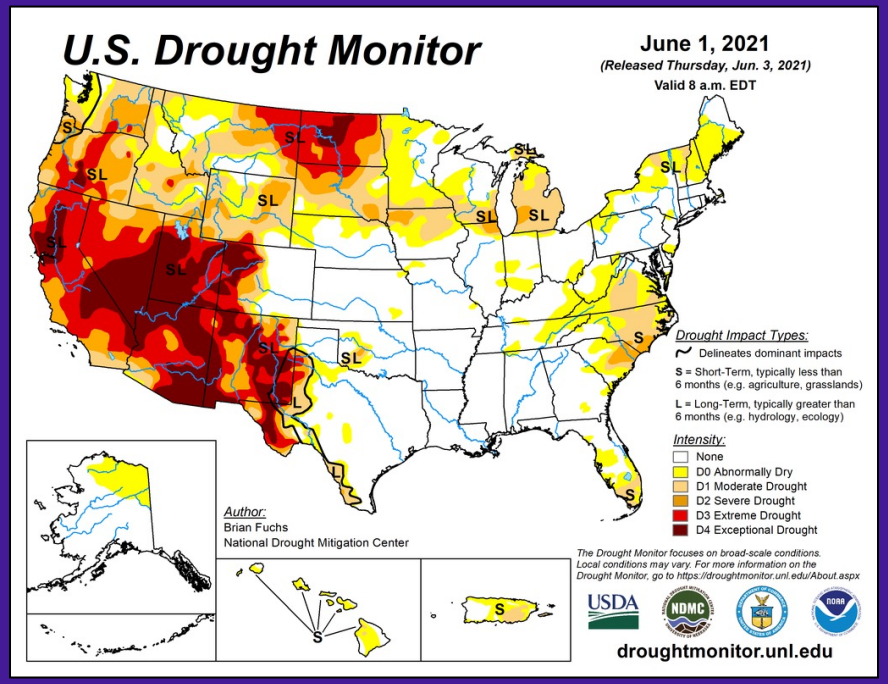
- Terra MODIS under lowering orbit will step into a critical 30-year thresholds allowing for more precise delineation of subtle climate trends and analysis of hotspots of change.

- Analysis of trends in coincident data products (snow cover, Evapotranspiration and Land Surface Temperature), can we identify “hotspots” of drought-related activity, to inform models and thus formulate the **societal response** needed to mitigate effects of the megadrought in local areas.

- The combination of increasing LST (warming) and declining ET and snow cover is intensifying climate aridity and **drought severity** in California and the southwestern U.S. (Hall et al.)

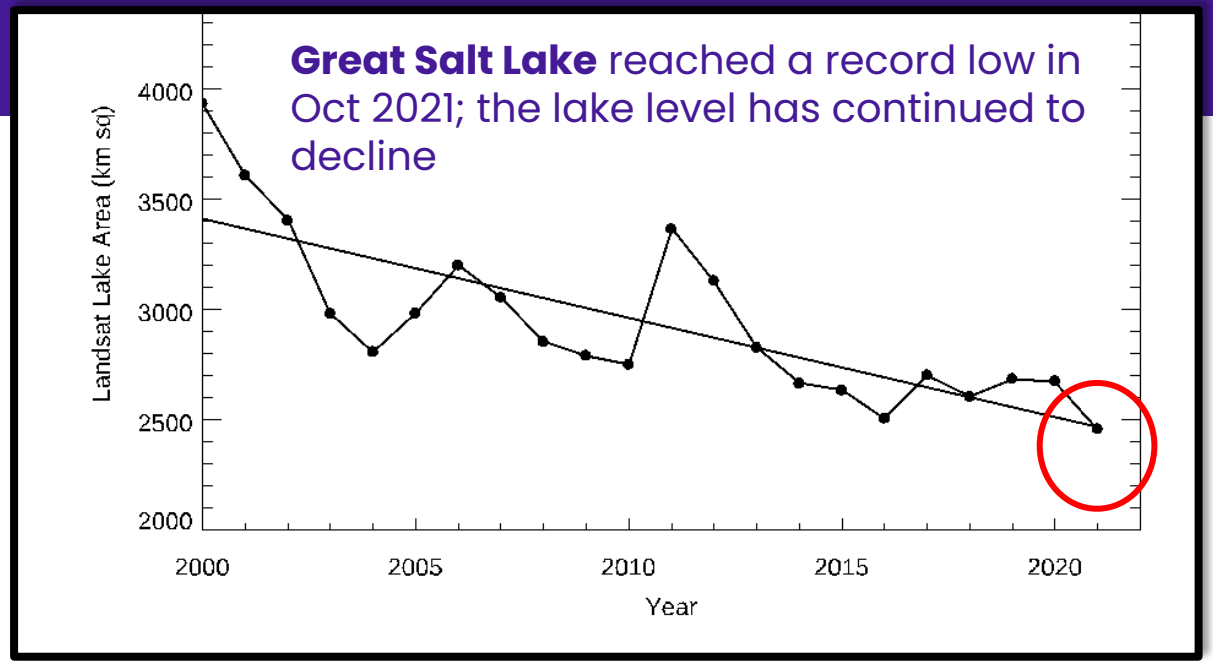
Megadrought in the U.S. West

- A decades-long drought in the southwestern U.S. began the year of the Terra launch (1999)
- One effect has been desiccation of saline lakes
- We have used ESDRs from diverse, coincident and validated MODIS data products to understand environmental conditions associated with the drought

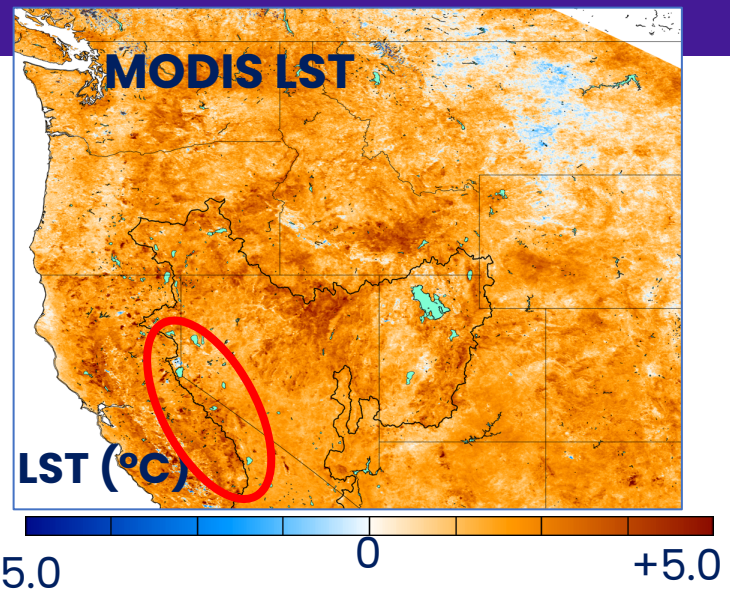


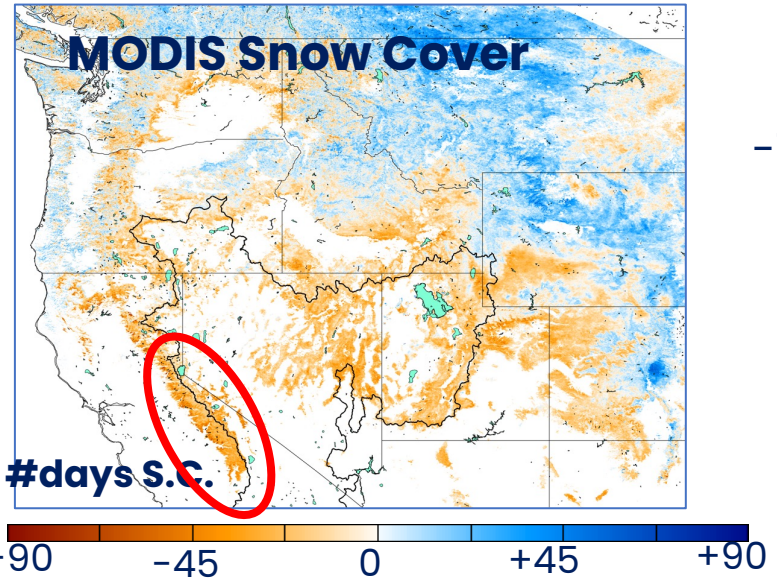
Note the large areas of ***Exceptional Drought*** in the Southwest US.

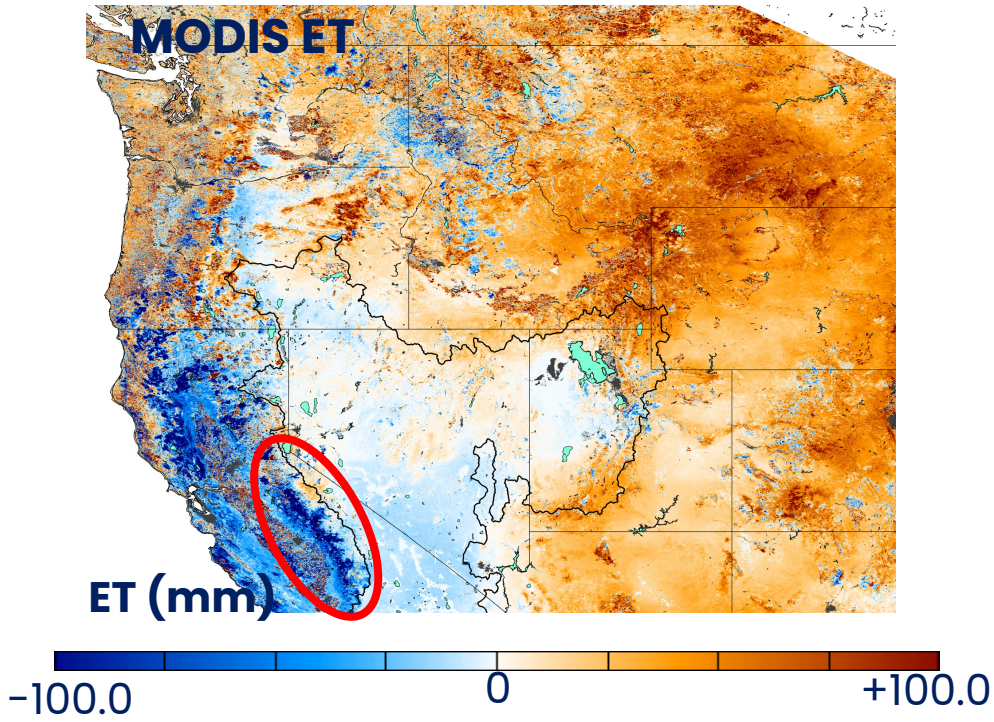
Saline lakes turn red from *Halobacteria* when water levels get low and salinity gets too high. Photo: Lake Abert, OR, 30 July 2014, R. Larson.



MODIS ESDR trend maps show a dramatic increase in LST, while snow cover and ET trends are mixed in the western U.S., 2001 - 2021







MODIS ESDRs enable identification of "hot spots" of extreme drought-related changes, e.g. Sierra Nevada Mts. (incl. Mono Lake basin):

- +2.3°C mean **LST** increase
- -23.7 (fewer) days persistent **snow cover**
- -26.5 mm **ET** decrease

ET increases in areas where water supplies are adequate to sustain greater evaporation, but ***decreases*** in the severe drought areas of California and the Great Basin where vegetation is becoming increasingly sparse and soils are drying.

From: Hall, D.K., J.S. Kimball, R. Larson, N.E. DiGirolamo, K.A. Casey & G. Hulley (submitted): Intensified warming and aridity accelerate terminal lake desiccation in the Great Basin of the western United States.

Leveraging MODIS observations during orbital drift to characterize the diurnal variations of lake vertical temperature profiles and evaporation rates

Huilin Gao and Shuai Zhang, Texas A&M University

Background: MODIS Global Water Reservoir Product (MxD28)

https://modis-land.gsfc.nasa.gov/modgwr.html

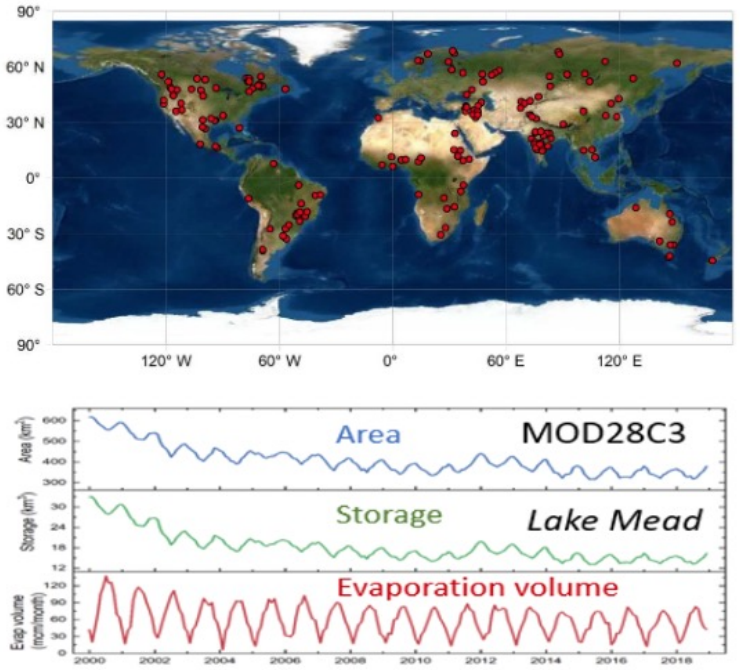
Li et al, 2021 *Remote Sensing*

Water Reservoir

The MODIS Water Reservoir product includes time series of surface area, elevation, storage, evaporation rate, and volumetric evaporation. The MOD28 reservoir surface area algorithm is based on image classifications of NIR reflectance from both Terra (MOD09Q1) and Aqua (MYD09Q1). The storage and elevation values are calculated by applying the area to the pre-established Area-Volume-Elevation (AVE) curves for each reservoir of interest. The MOD28 reservoir evaporation rate is estimated using the newly developed Lake Temperature and Evaporation Model (LTEM). In the LTEM the MODIS LST data (MOD11A2 and MYD11A2) are employed to constrain the modified Hostetler Model for calculating lake water temperature profiles. The temperature profiles were then used to calculate lake heat storage change term in the Penman equation. The calculation of the evaporation rate also requires gridded meteorological inputs from GLDAS and bathymetric data. The volumetric evaporation is calculated as the product of the evaporation rate and surface area.

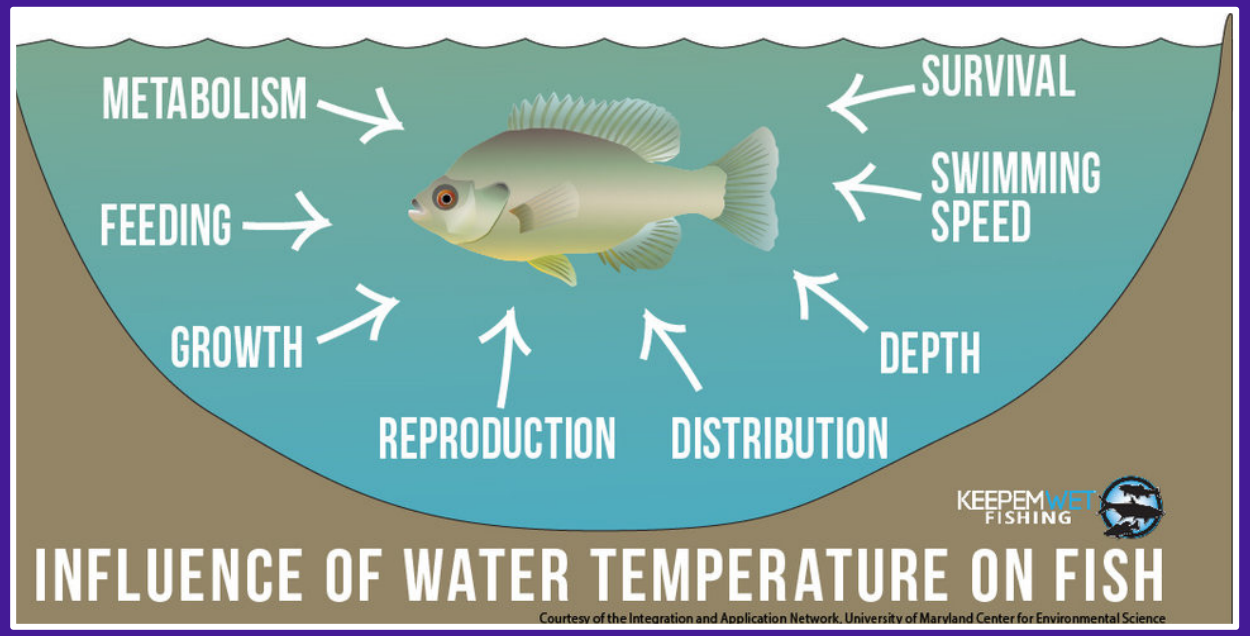
This product provides data for 164 global reservoirs. It includes 151 man-made reservoirs (2,672 km^3) and 13 regulated natural lakes (23,801 km^3). The total storage capacity of the 151 man-made reservoirs represents 45.82% of the global capacity (in its category) according to the Global Reservoir and Dam Database (GRanD). The MOD28 product is available as both an 8-day and a monthly temporal resolution, however, the evaporation rate and volumetric evaporation parameters are only available in the monthly product. All of these estimates are made available in tabular form, using the VDATA model in HDF format.

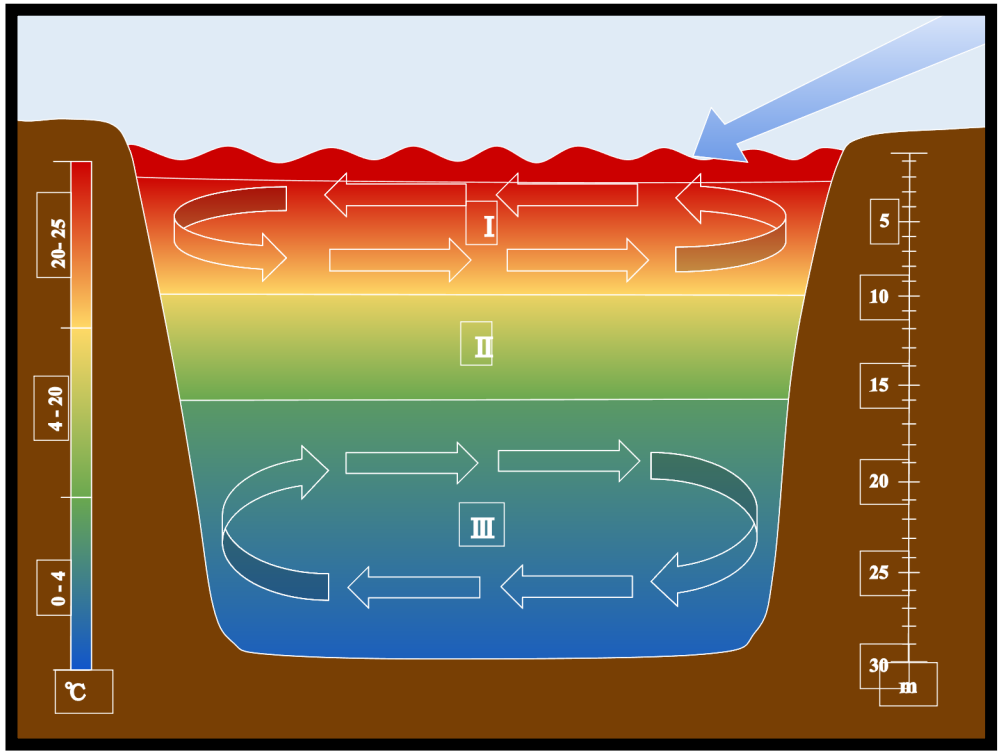
These MODIS reservoir observations can be used to support various applications, such as hydrological monitoring and modeling, water resources management, and Earth system modeling.



Vertical lake temperatures have a significant impact on aquatic ecosystems:

- Serve as an indicator of lake stratification
- Affect the vertical distribution of zooplankton
- Have an impact on fisheries



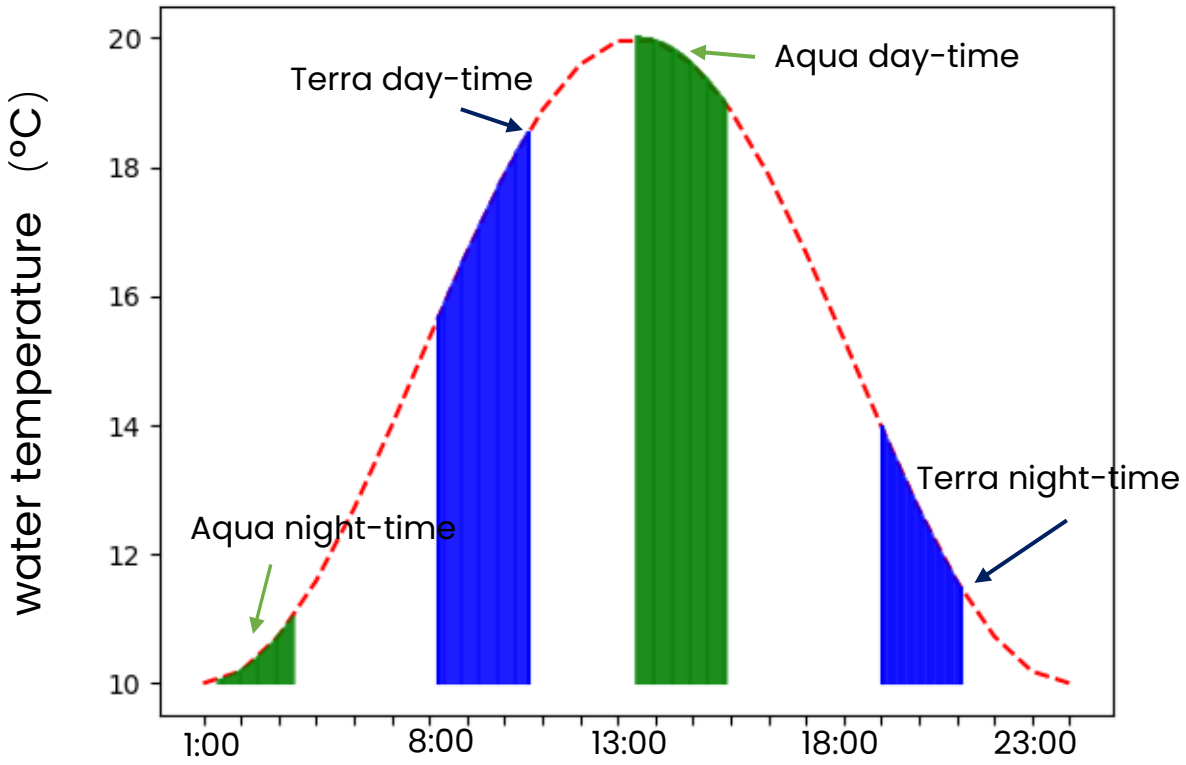


Lake stratification may intensify lake warming and worsen the water quality

(Woolway et al., 2021, *Nature Communications*; Woolway et al., 2022, *BioScience*)

Potential approaches:

•MODIS surface temperature + lake temperate model (data assimilation)
•MODIS observations + data from other satellites (data fusion)



Schematic diagram of diurnal water temperature change

The unique opportunities provided by the MODIS data during orbital drift

(1) Improve LTEM for characterizing diurnal lake vertical temperature profiles.

(2) Quantify the diurnal variability of evaporation rates for medium/large lakes (i.e., those that are observable at MODIS resolution).

(3) Establish a data fusion framework by fusing satellite observations with different overpass times

Potential interested science communities and decision makers

climatologists, hydrologists, biologists, environmental scientists

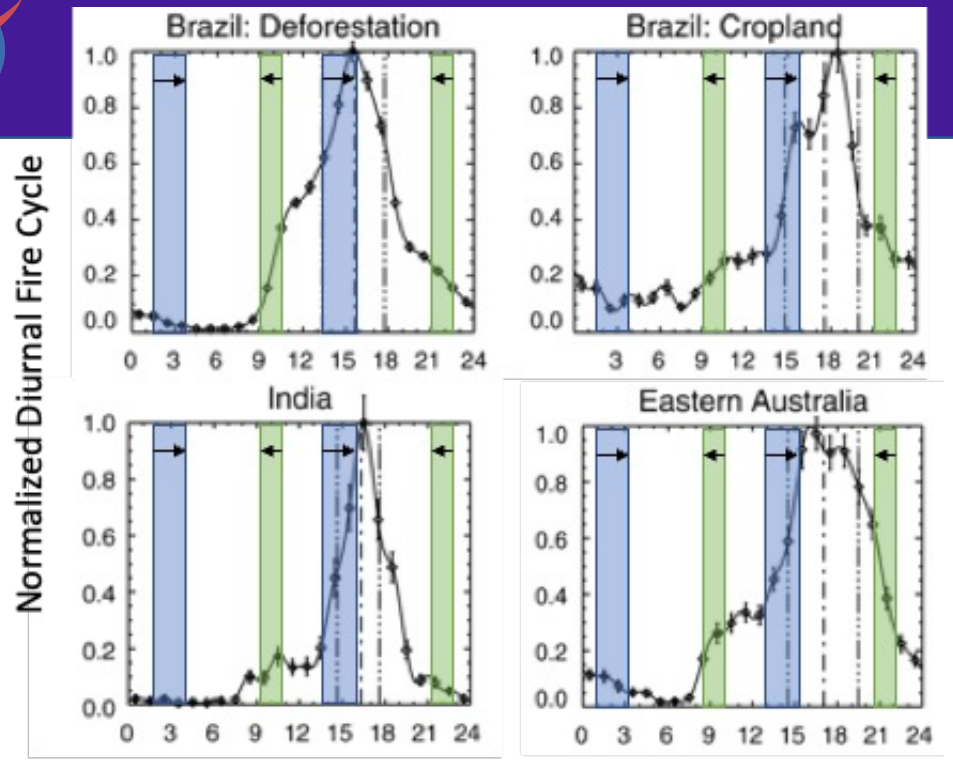
Federal and international agencies, fishery industry and water resources decision makers

Terra/Aqua MODIS Orbital Drift Enables Novel Fire Science and Applications

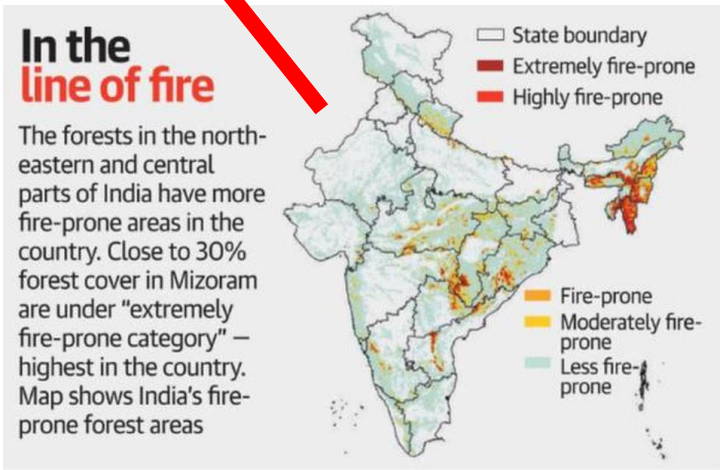
Douglas Morton*♦, Joshua Johnston*#, James Randerson♦, Andrew Hudak, Mark de Jong*, Elizabeth Wiggins♦, Denis Dufour*, David Peterson, David Saah♦, Robert Field♦, Benjamin Poulter, Louis Giglio#, Melanie Follette-Cook♦, Wilfrid Schroeder#, Shane Coffield♦, David Roy#, Brendan Rogers, Nancy French, Martin Wooster#

* CEOS WG Disasters Wildfire Pilot, ♦ NASA EIS-Fire, # GOFC-GOLD Fire Implementation Team

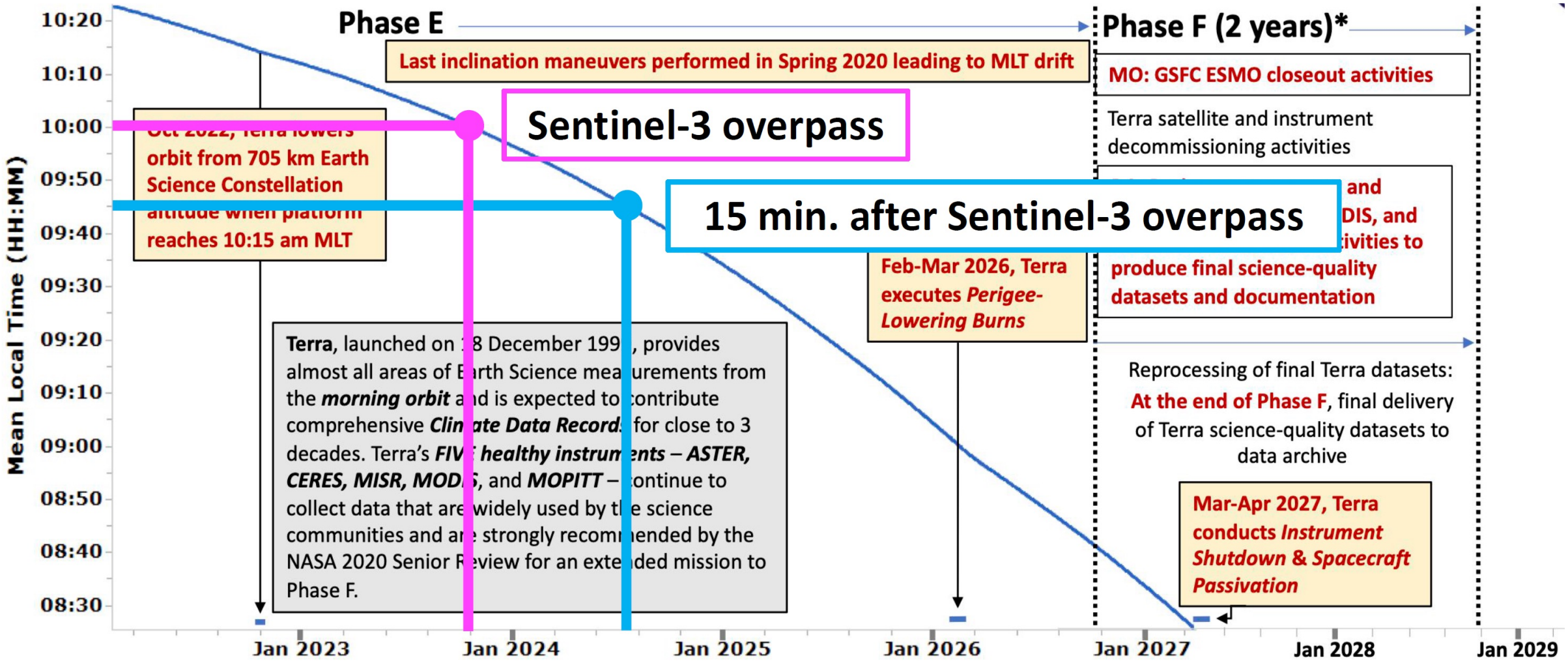
- **At novel times:** Terra and Aqua drift data will sample longstanding data gaps when fires are most common (**upper**, data from Giglio 2007) and often most intense (**lower**, data from GOES, Wiggins et al., in prep) to understand new extreme fires and small fires that worsen air quality where people live.
- **From repeat sampling:** Growing time offsets between MODIS & VIIRS will track sub-daily behavior of large fires needed to build and test the next generation of fire spread models.
- **With multi-sensor observations**: MODIS, MISR, MOPITT, and ASTER provide complementary data to advance fire science.
- **To optimize future missions:** Terra and Aqua orbital drift data will help optimize overpass times and algorithm development for future dedicated wildfire monitoring systems (e.g., WildFireSat) and permit cross-calibration with ESA's Sentinel-3 fire products (10:00/22:00) to extend the Terra data record.

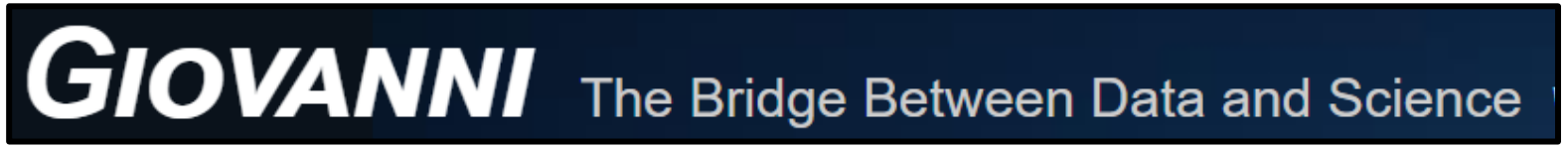


One-fifth of India's forests are now prone to fires due to a changing climate.



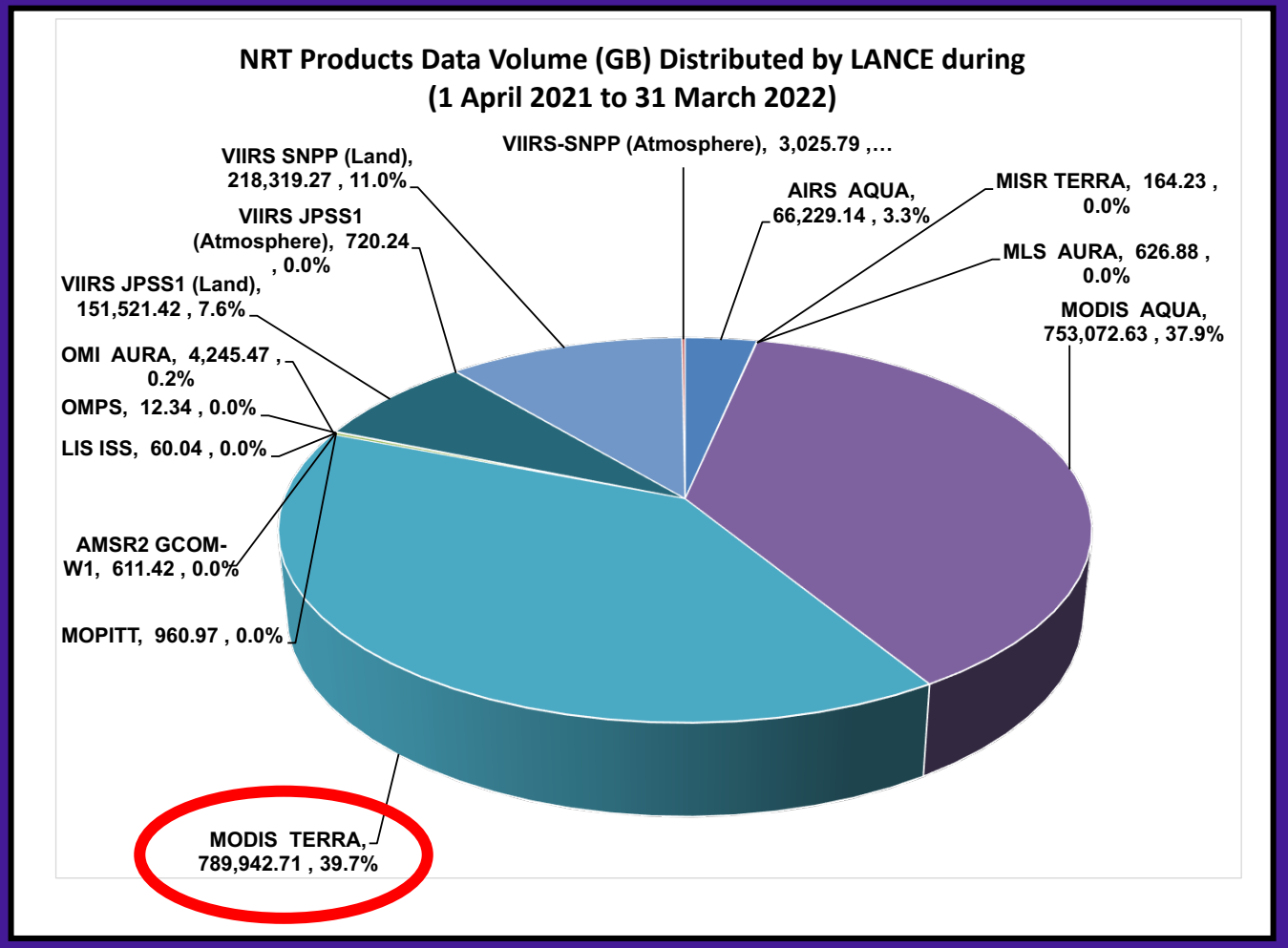
Terra Timeline if Maximally Extended relative to Sentinel 3

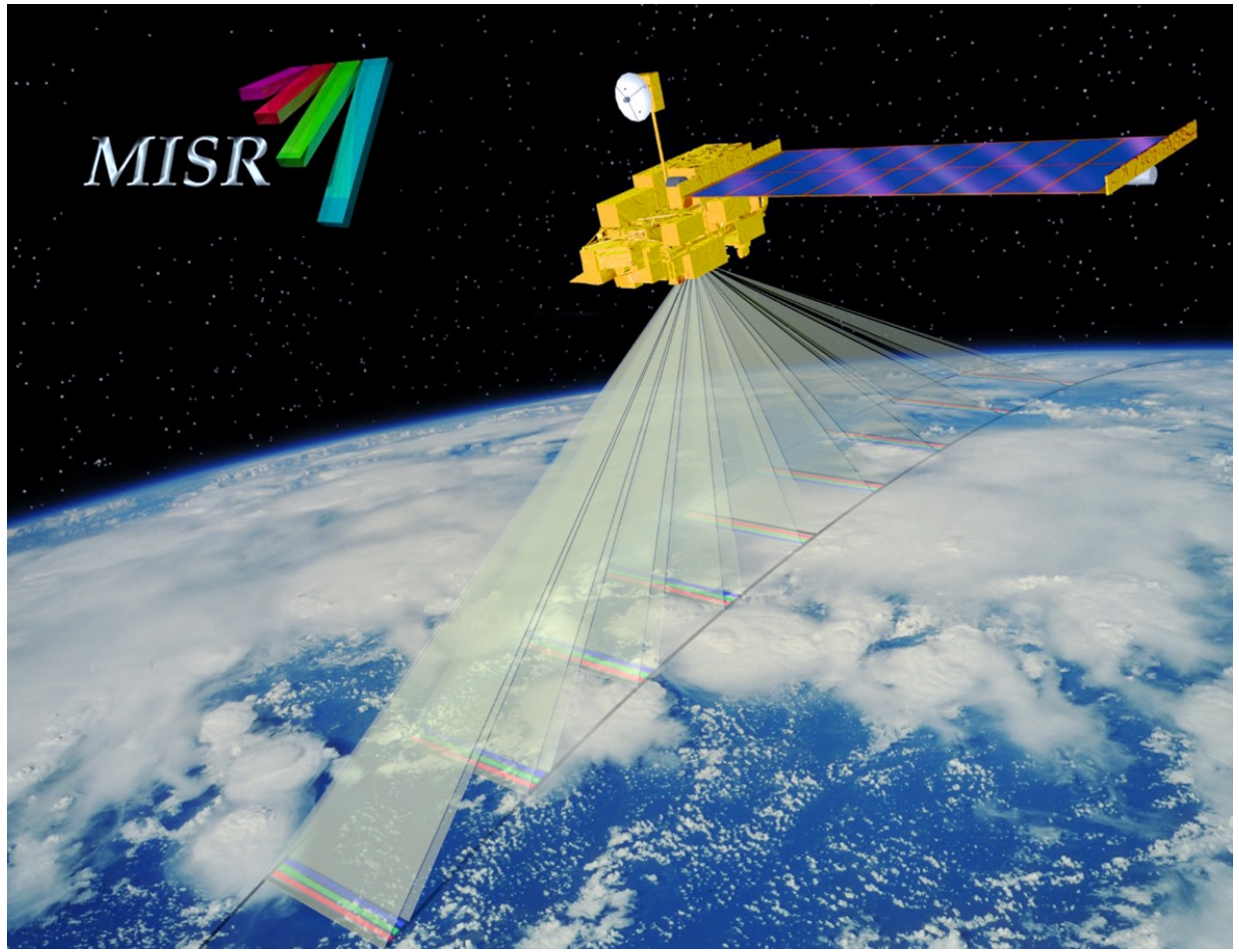




Terra MODIS Contribution Goes Beyond Science

Terra MODIS Contribution Goes Beyond Science





MISR: Impacts and opportunities of Terra orbit changes

Terra Lower Orbit Community Forum
December 8, 2022

David J. Diner, Michael Garay, Earl Hansen, Veljko Jovanovic

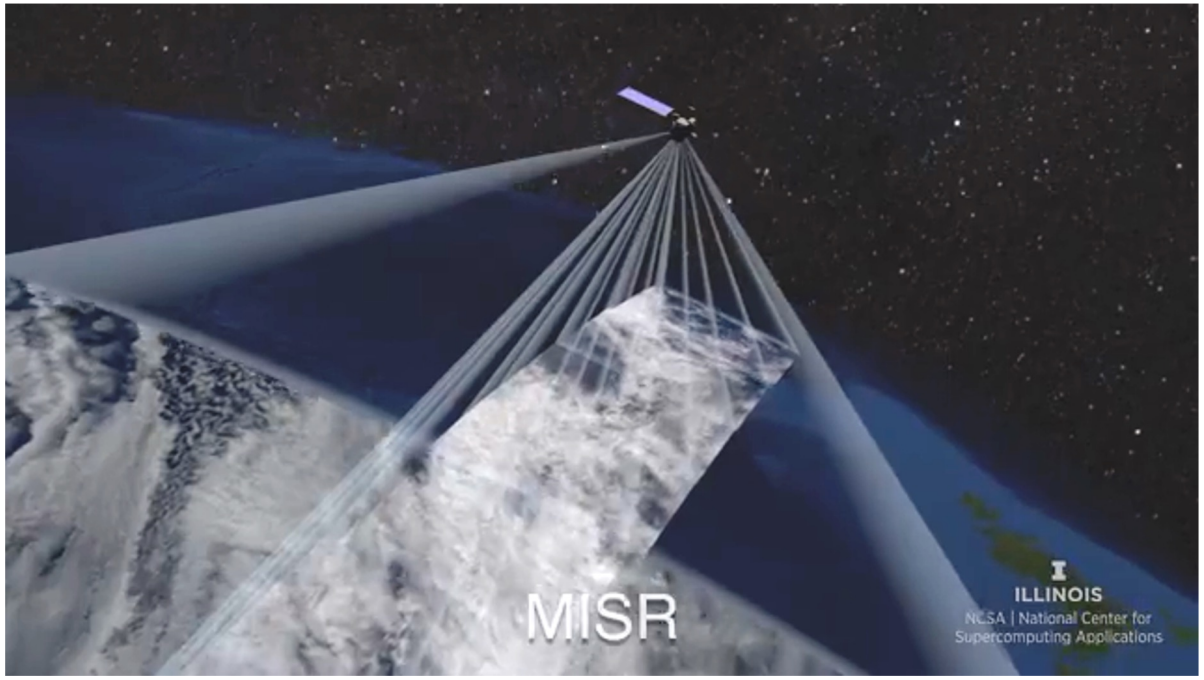
Jet Propulsion Laboratory
California Institute of Technology

Jeff Walter
NASA Atmospheric Science Data Center

and the MISR Team

MISR status

- Multi-angle Imaging SpectroRadiometer
- 9 view angles between ±70º
- Four spectral bands: 446, 558, 672, 866 nm
- 7-minute time lapse between views
- 275 m – 1.1 km sampling
- ~400 km swath – global coverage in 9 days



Bimonthly calibration sequences using the on-board calibrator continue routinely.

- Reliance on stable photodiode detectors to measure reflected sunlight from Spectralon panels preserves accurate radiometric calibration despite changes in solar illumination due to MLT drift.

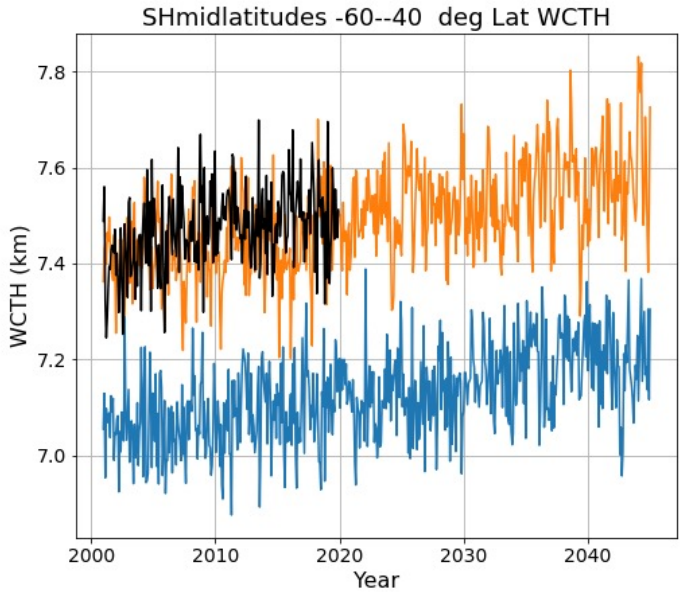
The MISR instrument is operating in excellent health and continues collecting science data since the orbit maneuvers were completed.

MISR uniqueness

Major MISR capabilities were highlighted in NASA's Terra, Aqua, Aura Drifting Orbits Workshop (November 1-2, 2022) and in responses to the associated RFI:

- **Stereographic cloud-top and smoke/dust/volcanic plume height retrievals, independent of instrument calibration and atmospheric temperature structure**
  - Applications: cloud response to climate change, aerosol plume hazards, plume-rise model validation, and characterization of wildfires on air quality and regional climate
- **Aerosol particle property retrievals over land, including characterization of particle size, shape, and light absorption**
  - Applications: validation of aerosol type differentiation in climate models, distinction of natural from anthropogenic particles in climate and air quality studies, and mapping of compositionally differentiated airborne $PM_{2.5}$ for health impact investigations
- **Moderately high resolution BRDF observations of clouds and surfaces**
  - Applications: hemispherical albedo calculations and 3-D cloud, vegetation, and ice-covered surface structure

Time series and spatial teleconnections of cloud-top heights



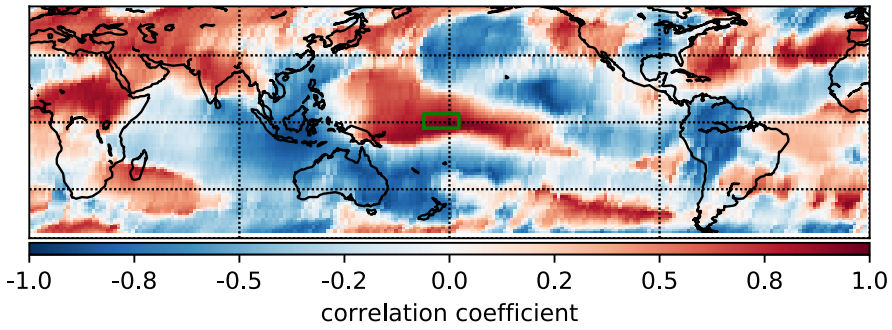
Statistically significant trends in high cloud heights are observed over the Southern Hemisphere

MISR Observations
IPSL-CM6A-LR
NCAR CESM2

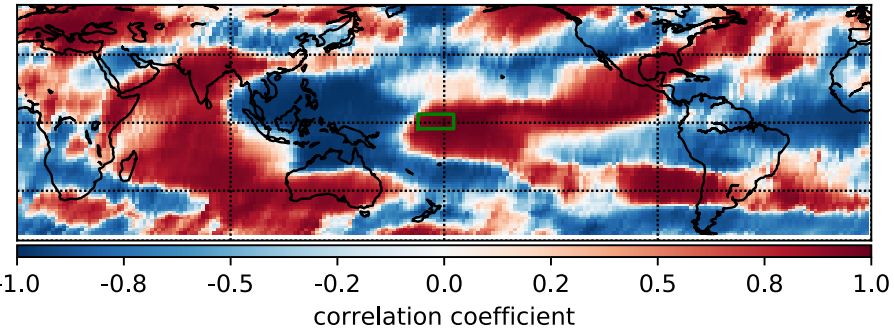
Aerenson et al. (2022)

Central Pacific height variability shows patterns of spatial correlation with other areas of the globe

Correlation with Central Pacific height anomalies



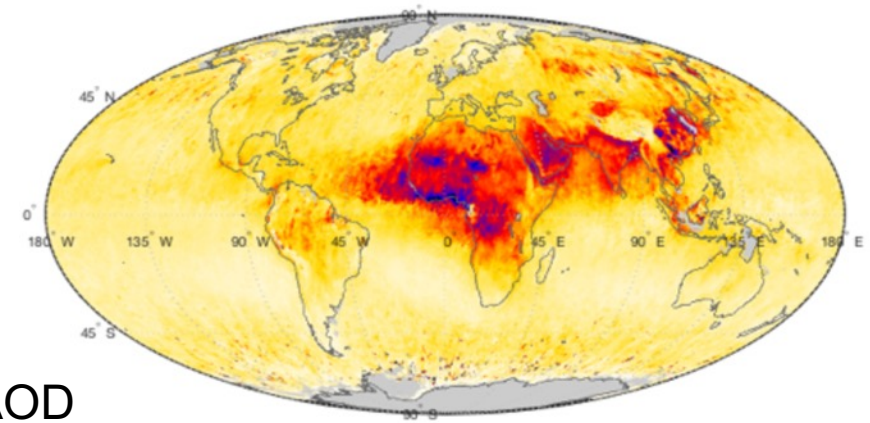
La Niña
5/11 – 4/12



Davies (2019)

El Niño
5/16 – 4/17

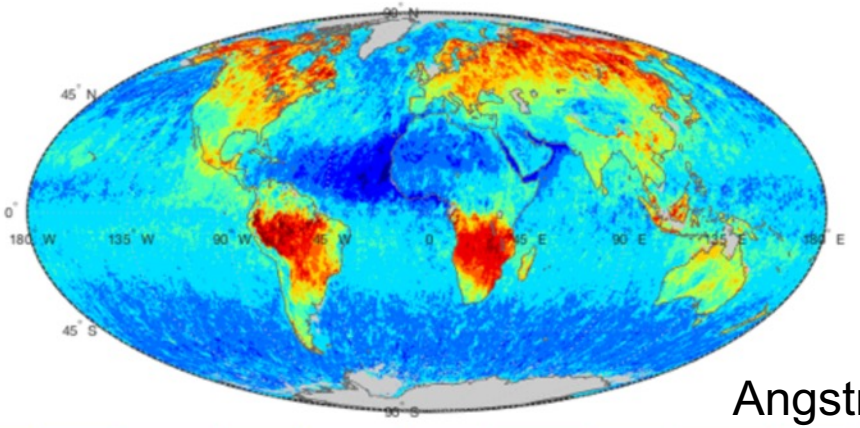
Aerosol abundance and particle properties



AOD

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8

more abundant →

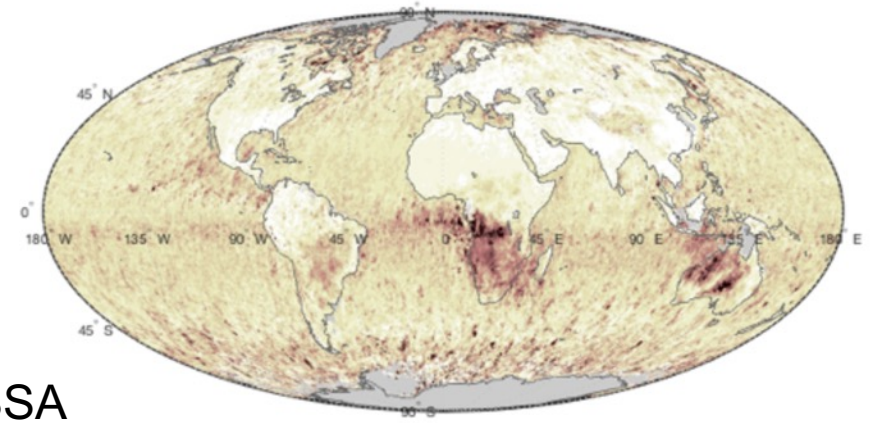


Angstrom exponent

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

← larger smaller →

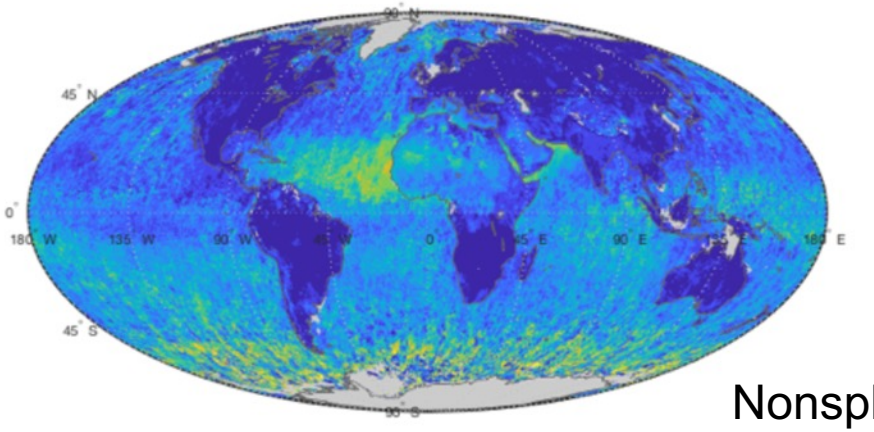
Garay et al. (2020)



SSA

0.9 0.91 0.92 0.93 0.94 0.95 0.96 0.97 0.98 0.99 1

← more absorbing



Nonspherical fraction

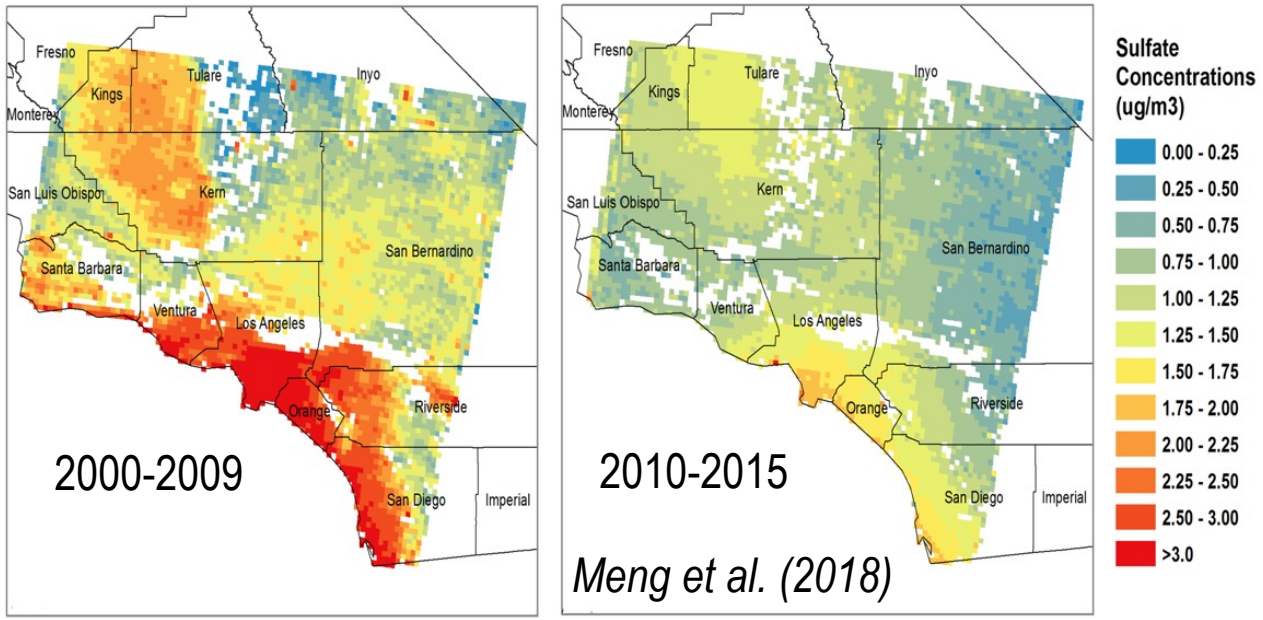
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

more abundant nonspherical →

Long-term trends in anthropogenic and natural aerosols

CALIFORNIA AIR RESOURCES BOARD

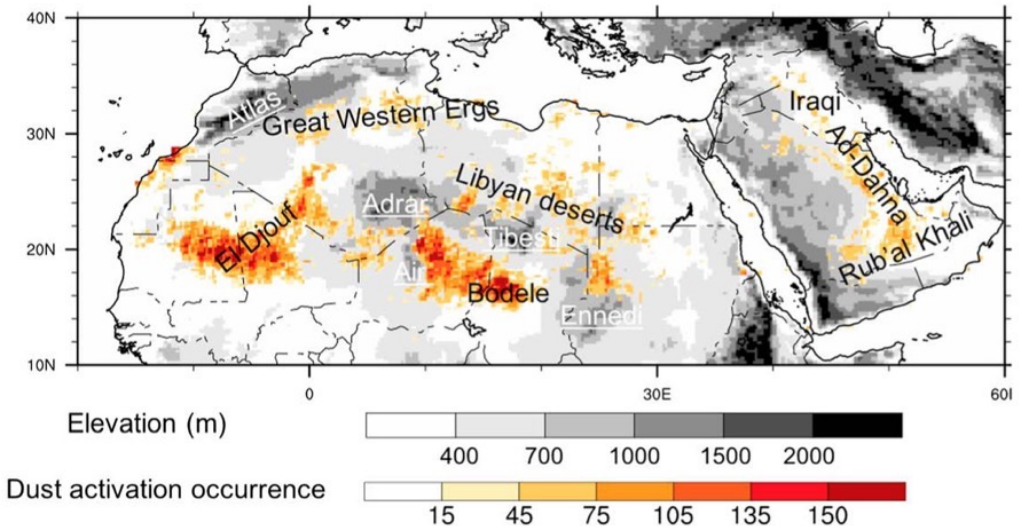
NASA satellite helps collect 15 years of Southern California air pollution data; results show air pollution controls working



Meng et al. (2018)

"This study provides new evidence that California's clean air programs are delivering reductions in air pollution in heavily-trafficked urban areas and in far-flung rural locations, including disadvantaged communities where people are hardest hit by pollution."
- *Bart Croes (CARB Research Director)*

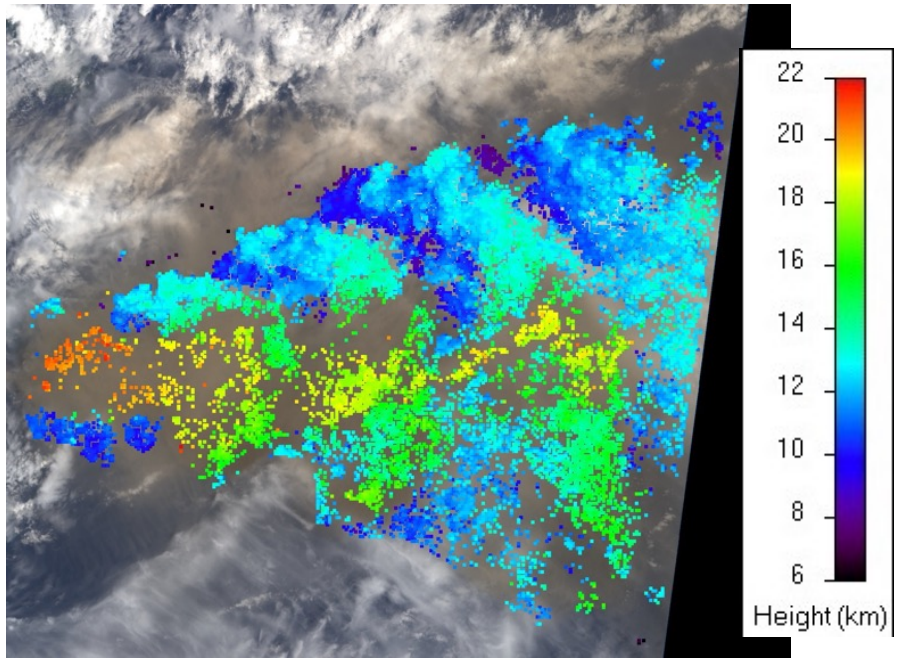
Dust concentrations have increased over the Middle East (15% yr^{-1}) and decreased over the Sahel (-12% yr^{-1}).



North African dust storms supply nutrients to the Amazon Rainforest.

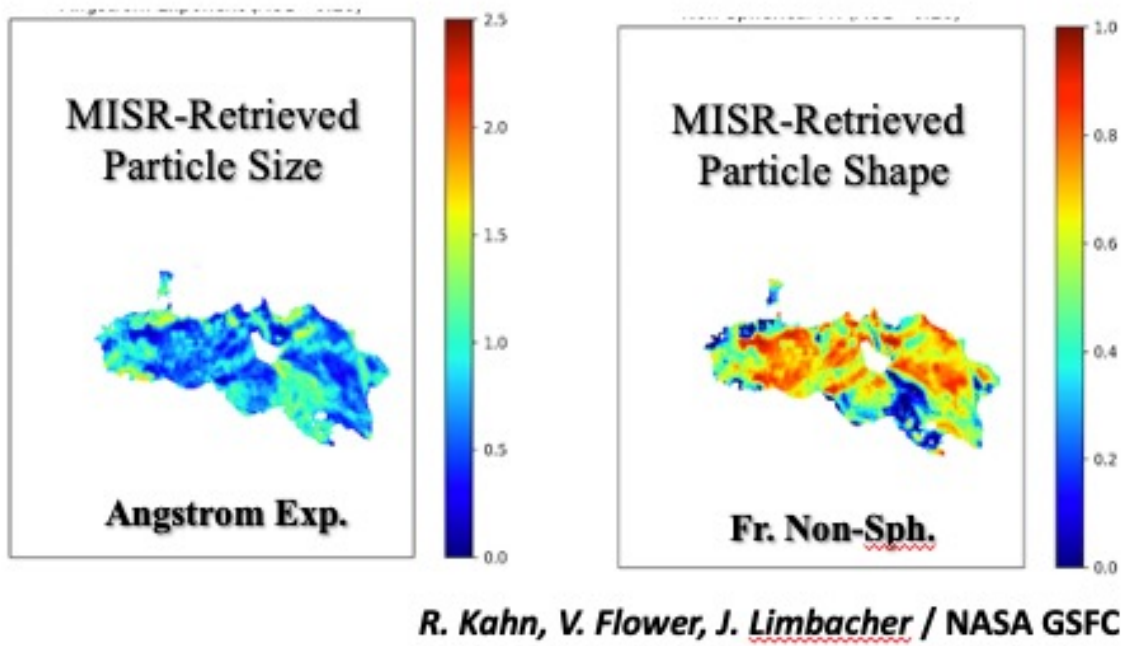
Yu et al. (2018, 2020)

Societal applications through contributions to disaster response – La Soufrière Volcano Eruption, April 2021



MISR Active Aerosol Plume-Height (AAP) Project

MISR's plume height map contributed to warnings issued by early responders and was used to initialize models of plume evolution used for generating ash transport forecasts.



MISR particle-property retrievals demonstrated that the volcanic plume was dominated by large, non-spherical ash rather than small-medium, spherical sulfate – therefore posing a hazard to aircraft and an air quality risk.

Impacts of change in orbit altitude on MISR data – 1

The largest impact of the lower altitude is that the orbit period no longer results in repeating ground tracks within the Worldwide Reference System (WRS-2).

- Reference imagery associated with each of the 233 WRS-2 paths was previously used to geolocate and co-register newly acquired data for all bands and angles.
- Because Terra no longer follows the exact WRS-2 paths, modified algorithms to preserve georectification and co-registration accuracies using ray casting in conjunction with globally distributed Ground Control Points were developed and tested prior to the orbit maneuvers.

The lower orbit has negligible or minor impact on:

- The 275 m map-projected spatial grid (data are resampled to this grid)
- The imaged swath width, which narrows by <1%
- View zenith angles; these are handled in the data processing algorithms

Impacts of change in orbit altitude on MISR data – 2

As a consequence of the orbit maneuvers:

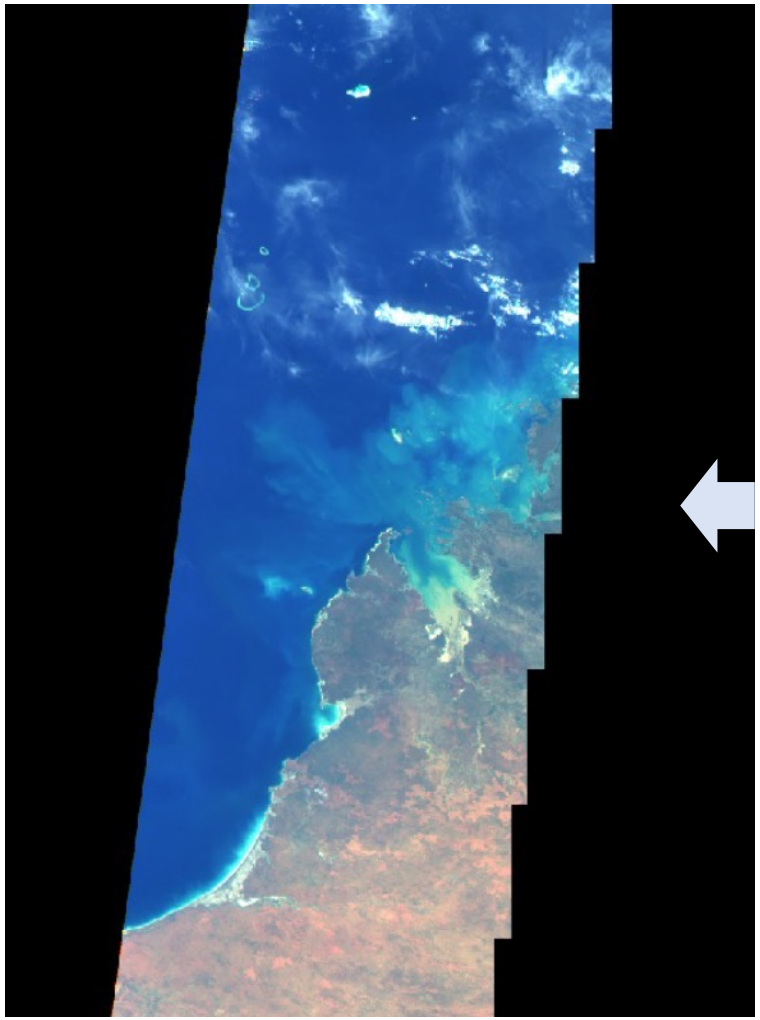
- A shift in the geometric model of one of MISR's 9 cameras occurred. The model has been re-calibrated and is undergoing verification.
- The automated job handler for the operational product generation software pipeline at ASDC required several additional modifications.

The science quality of MISR's data products is not affected by these technical issues; however, public posting of the products is on temporary hold until verification of the software updates is complete.

To minimize disruption to the user community, MISR data products will be reported on the *closest* WRS-2 path corresponding to the new Terra track.

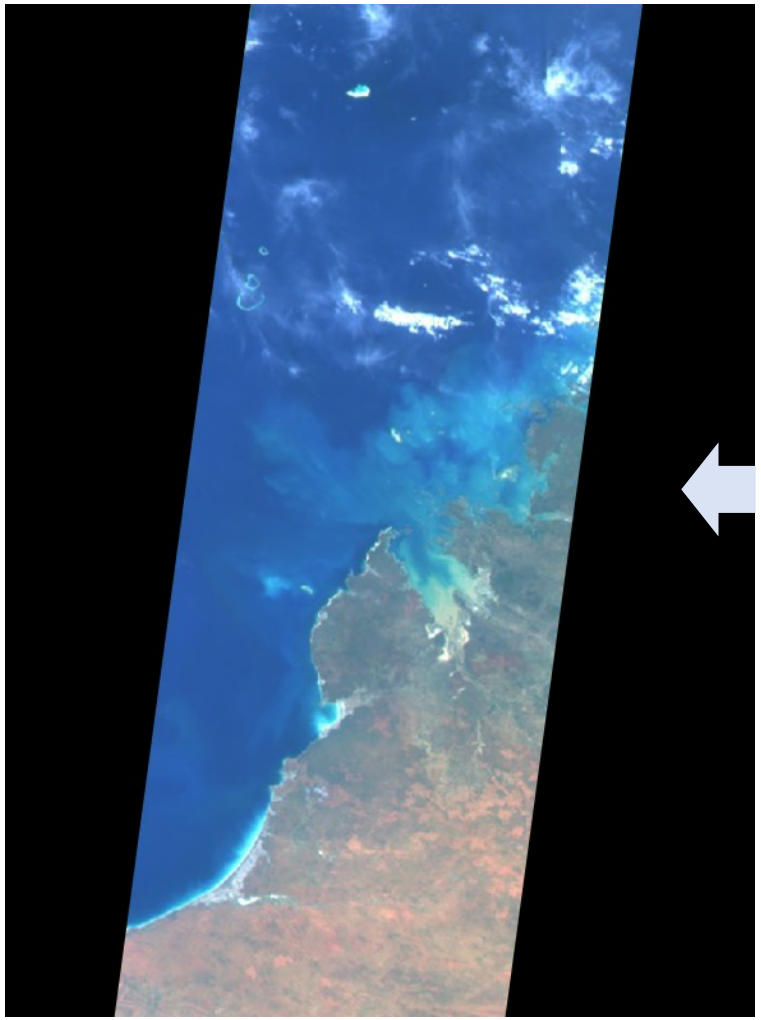
- The available projection area within MISR's data products is widened such that data for each orbit do not get truncated.

Comparison of pre- and post-maneuver L1 data production algorithms



Original algorithm

- Mapped to WRS-2 path 111 for this orbit
- Data are shifted from the Terra track
- Geolocation accuracy reduced
- Data truncated at edge of FOV



New algorithm

- Dynamically mapped to WRS-2 path 110 for this orbit
- Data are centered on the Terra track
- Geolocation accuracy maintained
- Data preserved at edge of FOV

Post-maneuver orbit 121418 (October 16, 2022).
Data were processed through the software pipeline at ASDC.

Applications with minimal impact from MLT drift – 1

Area of study	Findings in MISR record	Value of extended record
High cloud trends and climate feedbacks: Climate models predict high-cloud heights to shift upward, providing positive feedback.	Upward trend in high-cloud height is observed in the Southern Hemisphere but not in the Northern Hemisphere.	Improved statistical significance helps climate model evaluations and understanding of these hemispherical differences.
Variability in global atmospheric circulation: Many known modes of atmospheric variability affect cloud cover and the Earth's radiative budget.	Global-scale teleconnections in cloud heights are observed in conjunction with ENSO. Linkages of cloud fraction to longer-period modes are also seen.	Understanding cloud response to synoptic variability on multi-decadal timescales provides novel ways to evaluate and improve climate models.
Air **quality and human health:** Airborne particulate matter (PM) is linked to numerous adverse health outcomes.	MISR and MODIS play prominent roles in the Global Burden of Disease study, which ranks PM as the top environmental health risk.	If extended into 2024, Terra will overlap with TEMPO and PACE; and if into 2025, with MAIA.

Applications with minimal impact from MLT drift – 2

Area of study	Findings in MISR record	Value of extended record
Disaster response: Aerosol plumes from wildfires, volcanic eruptions, and dust storms pose hazards to human life and property.	MISR plume heights and particle properties provide input to responders and air quality forecasters.	Severity of wildfire events is increasing and significant volcanic eruptions can occur at any time.
Coordination with field campaigns: Spacecraft-aircraft coordination is essential for process studies.	Terra has historically added major value to sub-orbital campaigns, most recently NASA's CAMP2Ex.	If extended at least through 2024, Terra will support ARCSIX and other near-term campaigns.

Novel opportunities associated with MLT drift – 1

Area of study	Findings in MISR record	Value of MLT drift
Diurnal variation in low-cloud height: Global climate models disagree on the response of low-level clouds to a changing climate.	No significant trend in cloud height has been observed at constant MLT.	Quantification of diurnal variation will test climate model predictions for clouds affected by solar heating.
Global cloud cover: Prior to EOS, it was impossible to decouple satellite instrument calibration issues from true diurnal variation.	Well-calibrated Terra instruments show small year-to-year variations over two decades at constant MLT.	Provides unprecedented opportunity for climate model evaluation at times of day with different proportions of stratiform and cumuliform clouds.
Cloud microphysics: Cloud droplet effective radius (CER) is one of the most important climate variables in studies of the indirect effects of aerosols on clouds.	Terra has quantified CER dependence on cloud structure and sun-view geometry by fusing SWIR observations from MODIS and multi-angle information from MISR.	Offers opportunities to improve CER accuracy over a wider range of cloud regimes and at different times of day.

Novel opportunities associated with MLT drift – 2

Area of study	Findings in MISR record	Value of MLT drift
Cloud and land surface radiative fluxes and 3-D structure: Angular bidirectional reflection models are used to calculate radiative fluxes, and characterize cloud, vegetation, and ice sheet structure.	Multi-angle flux consistency tests derived from MISR radiances collocated within the CERES footprint, have enabled quantitative evaluation of the CERES angular models.	Enables model evaluation over a larger range of illumination-view geometries and exploration of 3-D effects, which will be accentuated at earlier MLT.
Aerosol particle property retrievals from geostationary platforms: Fusion of data from multiple GEO platforms provides high temporal resolution multiangular sampling.	MISR has shown the value of multiangular observations for aerosol optical depth and particle property retrievals over land.	MISR is NASA's only imager than can be used to validate multiangular aerosol particle property retrievals over a range of morning hours.

Summary

MISR's well-calibrated, moderately high-resolution multiangular imaging approach enables a unique set of measurement capabilities, including:

- Stereographic cloud-top and smoke/dust/volcanic plume height retrievals
- Aerosol particle property (size, shape, light absorption) characterization over land
- Sensitivity to cloud and surface 3-D structure

No other instrument with this combination of capabilities currently flies in space, nor is a replacement envisioned in the near term.

The lower Terra orbit altitude does not affect the quality or utility of MISR data.

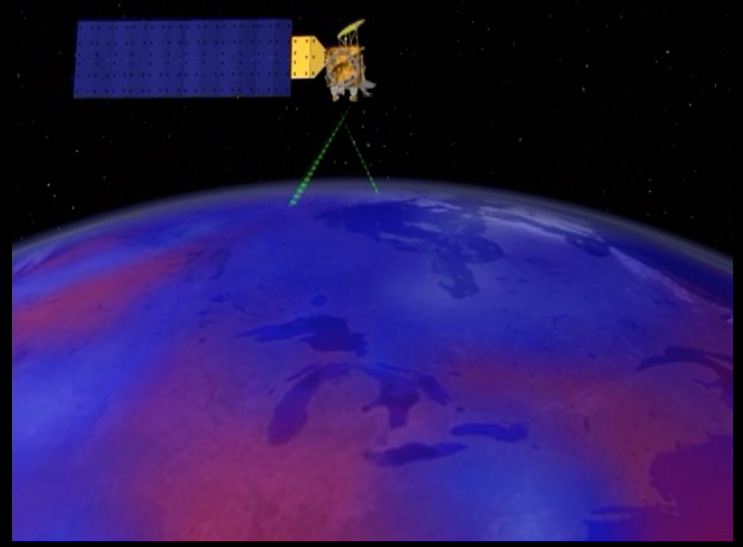
The drift in mean local time (MLT) of Terra equator crossing does not adversely impact the utility or quality of MISR's capabilities and offers numerous novel scientific opportunities.

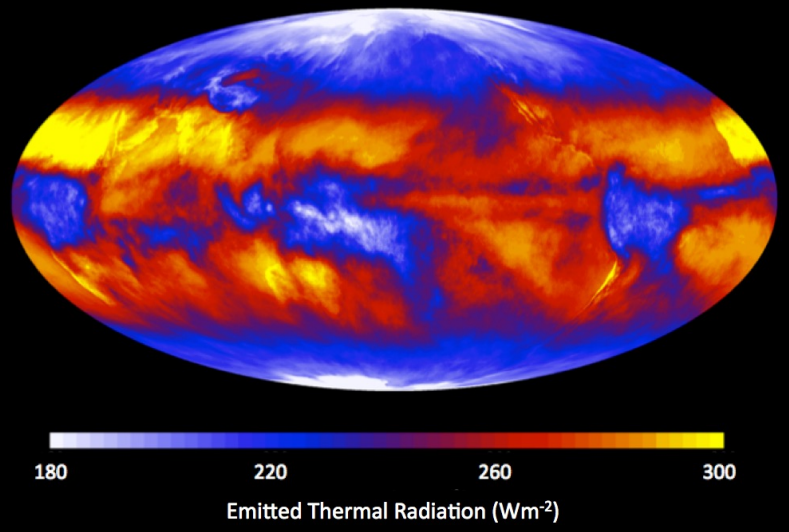
Clouds and the Earth's Radiant Energy System (CERES)

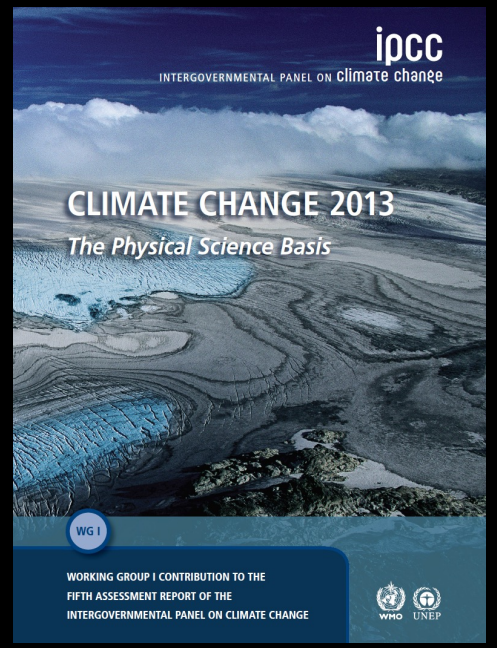
Norman G. Loeb
NASA Langley Research Center

Terra's Lower Orbit Virtual Community Forum, December 8, 2022

Clouds and the Earth's Radiant Energy System

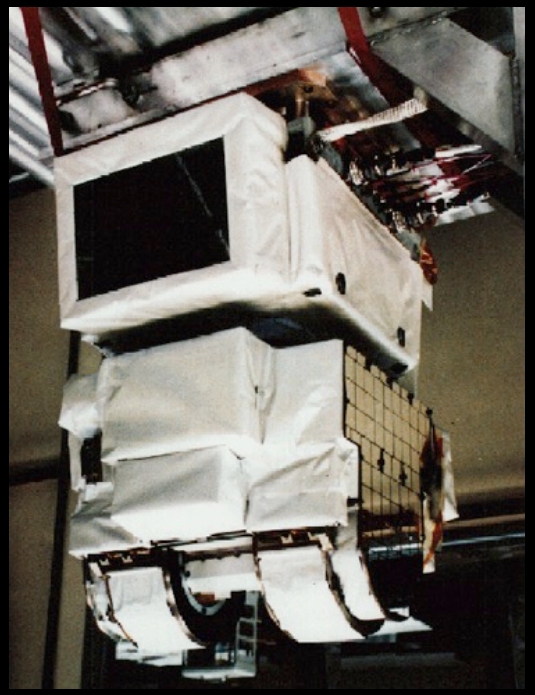






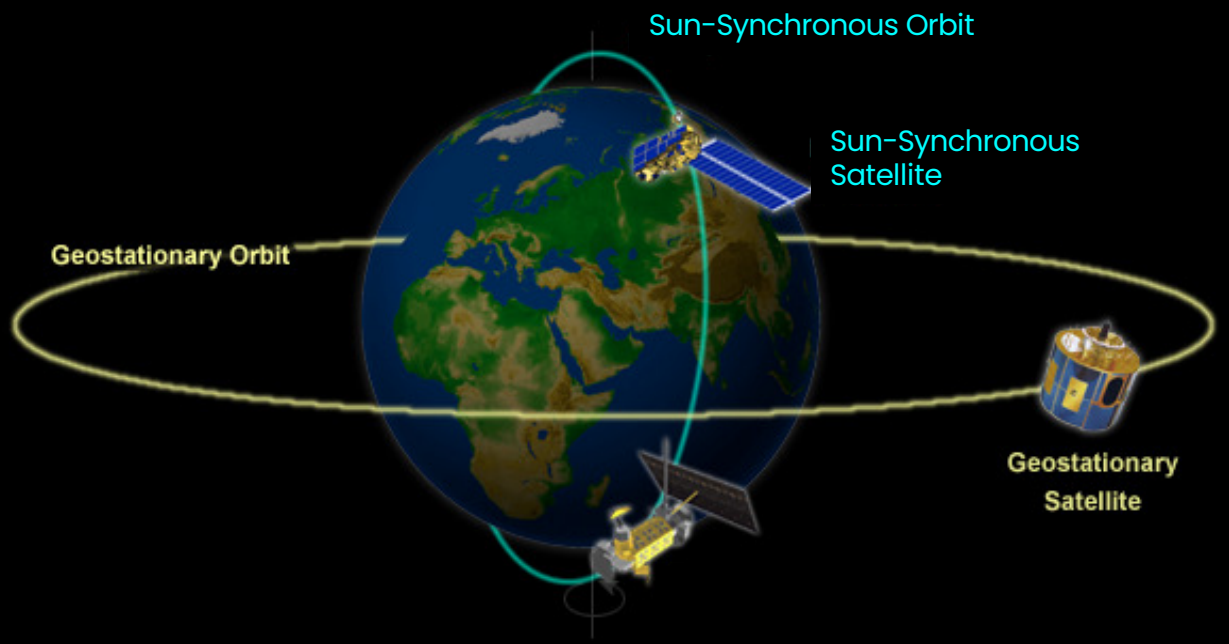
- Goal is to produce a long-term, integrated global climate data record (CDR) of Earth's radiation budget (ERB) from the surface to the top-of-atmosphere (TOA) together with the associated cloud, aerosol & surface properties.
- To enable improved understanding of the variability in Earth's radiation budget.
- To provide data products for climate model evaluation and improvement.

CERES Instruments



- 7 instruments on 5 satellites (TRMM, Terra, Aqua, SNPP, NOAA-20) for diurnal and angular sampling.
- Narrow field-of-view scanning radiometer with nadir footprint size of 10 km (TRMM); 20 km (Terra, Aqua), 24 km (SNPP, NOAA-20).
- Measures radiances in 0.3-5 mm, 0.3-200 mm and 8-12 mm (FM6 replaces WN with LW channel)
- Capable of scanning in several azimuth plane scan modes: fixed (FAP or crosstrack, rotating azimuth plane (RAP), programmable (PAP).
- Coincident Cloud and Aerosol Properties from VIRS/MODIS/VIIRS. Required for scene identification and addressing CERES science questions.
- Factor of 2-3 improvement over ERBE.
- All channels on CERES FM1 and FM2 are operating nominally.

Earth Radiation Budget Data Fusion



- In order to provide complete spatial coverage of Earth and resolve its diurnal cycle, a high level of data fusion is required.
- During the CERES period, the team has processed data from:
  - 7 CERES instruments
  - 1 VIRS imager (TRMM)
  - 2 MODIS imagers (Terra, Aqua)
  - 2 VIIRS imagers (S-NPP, NOAA-20)
  - 20 geostationary imagers
  - Solar irradiance measurements
  - Meteorological, ozone and aerosol assimilation data
  - Snow/ice maps

➢ **All data are integrated to obtain climate accuracy in radiative fluxes from the top to the bottom of the atmosphere.**

Expected Impacts of Orbit Lowering Maneuver

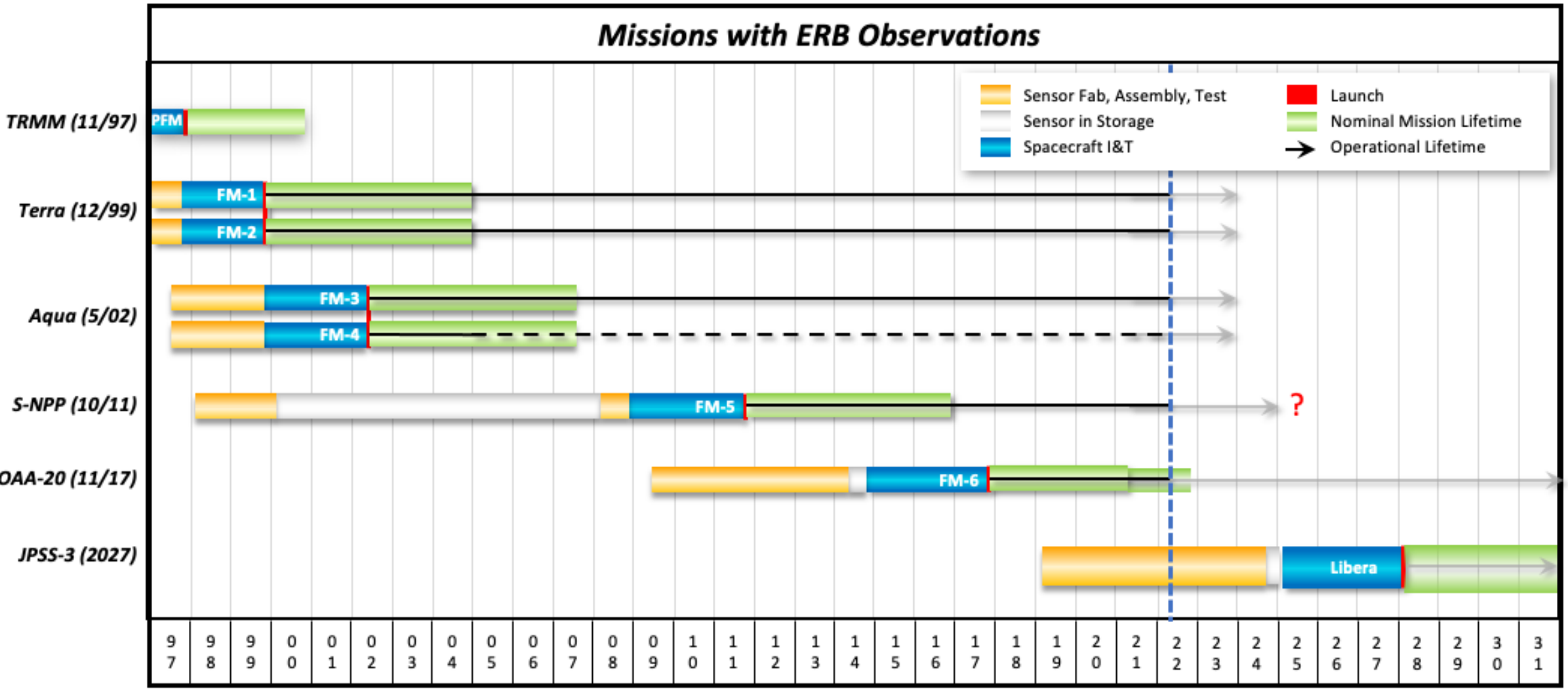
There is no impact to CERES data products resulting from the Terra orbit lowering maneuver.

CERES Terra Science Opportunities During MLT Drift

Gap Risk Analysis

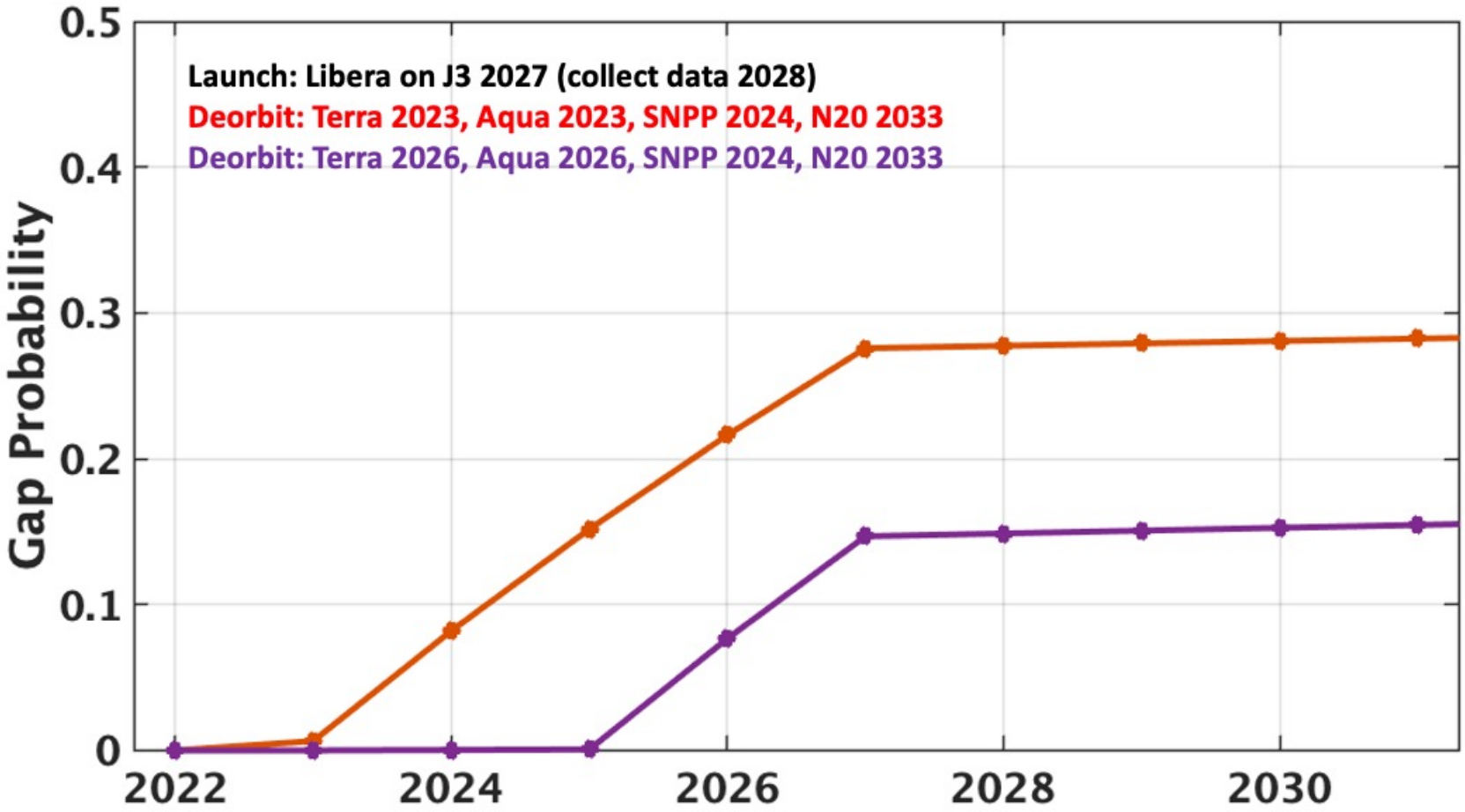
- Goal is to estimate of the probability that a data gap will occur in the Earth Radiation Budget climate data record given the ERB instrument flight schedule and historical spacecraft and instrument survival rates
- Period considered: present to 2032
- We assume that a mission terminates if either the ERB instrument, imager it flies with, or spacecraft fails.
- A further assumption is that an ERB instrument can bridge a data gap and maintain radiometric continuity of the ERB CDR even if its orbit drifts in mean local time (MLT) past its nominal mission requirement.

Flight Schedules



- Currently, 6 CERES instruments fly on 4 satellites: Terra (L1999), Aqua (L2002), SNPP(L2011), NOAA-20 (L2017)
- Libera scheduled for launch in 2028 on JPSS-3

Probability of a Data Gap in the Earth Radiation Budget Data Record

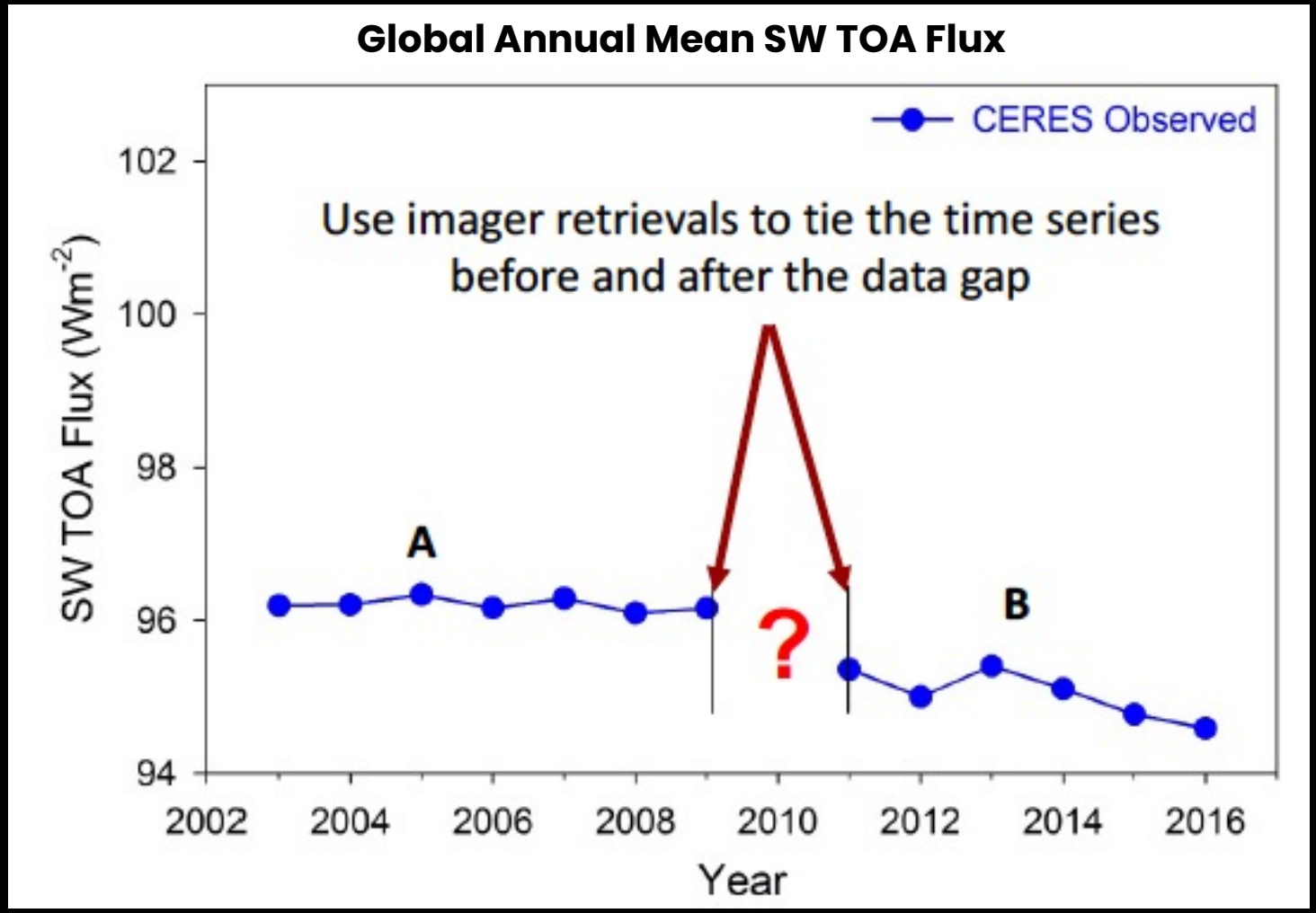


Probability of a data gap in the CERES climate data record assuming Terra and Aqua end science data collection in 2023 (red line) and 2026 (purple line). We assume SNPP and NOAA-20 end science data collection in 2024 and 2033, respectively, and Libera launches in 2028.

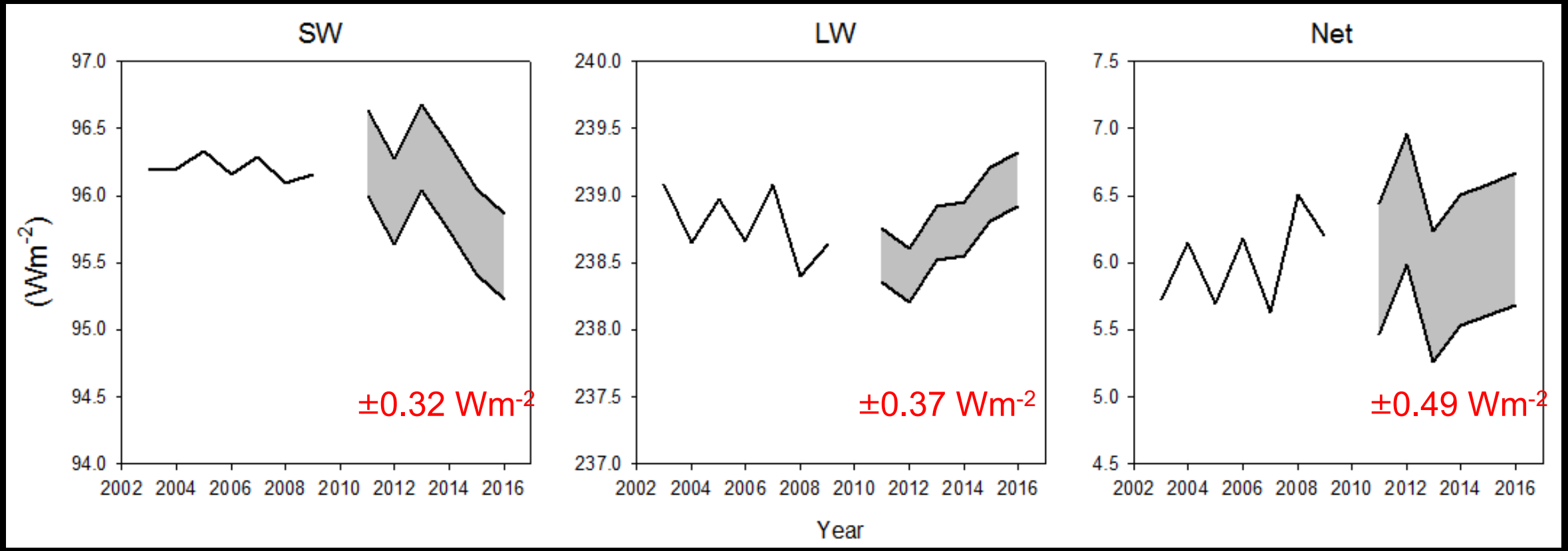
Bridging a Data Gap in the ERB CDR

Goal:

Examine the feasibility of using less-accurate imager retrievals to compute radiative fluxes and tie the time series before and after a data gap together.



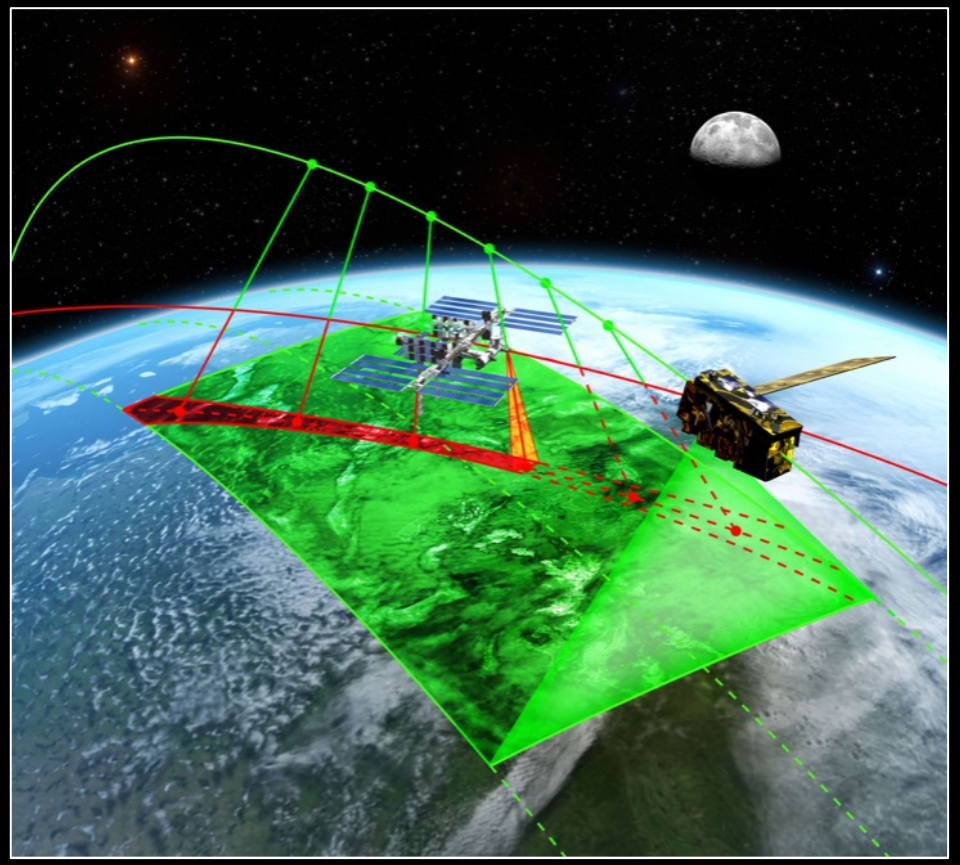
Bridging a Data Gap in the ERB CDR



- Assumes imager remains healthy and perfectly stable across the data gap.
- The longer the gap, the greater the risk.
- The resulting uncertainty is too large to enable decade-to-decade changes in EEI to be resolved.
- Time to detect a real trend above uncertainty would increase substantially.
- A gap would require considerable extra post-processing effort, thereby delaying release of the ERB data products.

Overlap with CLARREO-P

- Continuation of the Terra and Aqua missions ensures overlap with the CLARREO-P mission, currently expected to fly on the ISS in 2023.
- CLARREO-P consists of a highly accurate reflected solar spectrometer that will allow intercalibration of reflected solar instruments to within 0.3% (1 sigma) using space, time, spectral, and angle matched observations across the full scan width of remote sensing instruments, including CERES, MODIS, and VIIRS.
- If Aqua and Terra are still operational when CLARREO-P collects data, this will provide a one-time opportunity to place all reflected solar bands from CERES, MODIS, and VIIRS on the same radiometric scale set by CLARREO-P.
- This will dramatically improve the accuracy of climate data records from CERES, MODIS, and VIIRS, impacting countless geophysical variables (radiative budget, aerosol, cloud, vegetation, etc.) back to 2000, the start of the Earth Observing System (EOS).

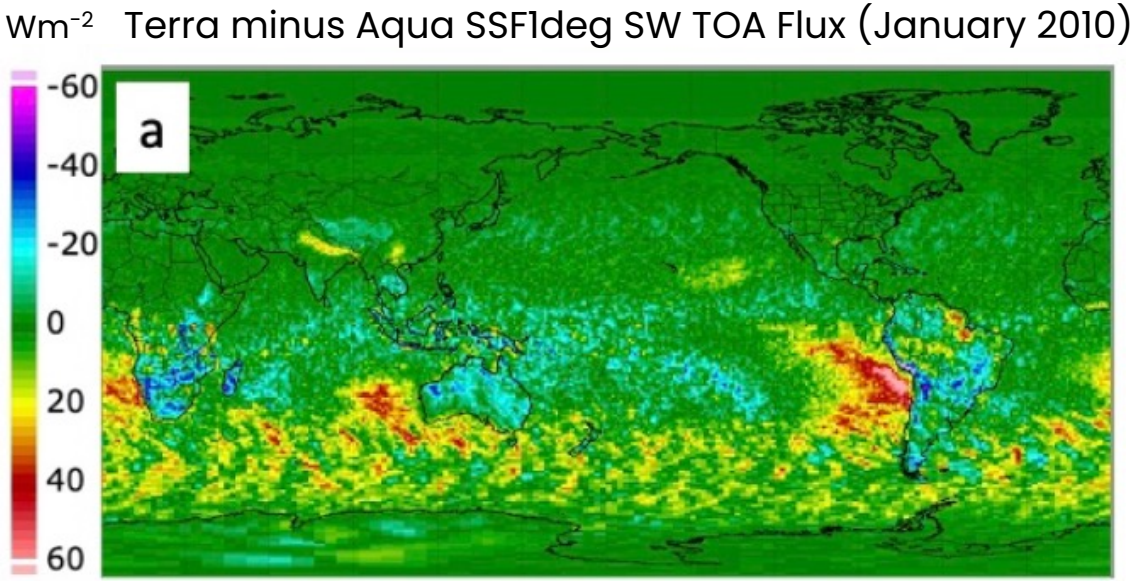


Improving Angular Distribution Models

- A slowly changing MLT for Terra will provide a unique opportunity to place one of the CERES instruments on Terra in RAP scan mode to extend the angular coverage of the CERES ADMs used to determine radiative fluxes from measured radiances.
- In RAP mode, CERES scans in elevation as it rotates in azimuth, thereby acquiring radiances over a full hemispheric range of viewing zenith and relative azimuth angle combinations. CERES RAP data acquired early in the Terra mission were used to construct CERES ADMs, which describe how TOA radiances normalized by flux vary with sun-Earth-satellite viewing geometry and scene type.
- Once the Terra MLT starts to drift, the CERES team will place CERES FM2 in RAP mode. This will significantly expand the solar zenith angle coverage of the CERES ADMs and enable past and future missions in orbits that differ markedly from Terra to produce accurate radiative fluxes.
- Over the past 15 years, the CERES ADMs have been a valuable community resource. Expanding the range of angular coverage will greatly increase their utility for many more groups interested in producing accurate radiation budget observations.

Benefits of Increased Diurnal Sampling: Time Interpolation

- One limitation of the current Terra and Aqua records of cloud properties and radiation flux derived from CERES and MODIS is that sun-synchronous twice-per-day measurements do not fully sample the diurnal cycle.
- Although geostationary satellites currently observe the entire diurnal cycle, they lack the wavelength range and calibration of CERES and MODIS and thus provide more limited information on the global climatological diurnal cycle of cloud properties and less accuracy in measuring radiation flux than would Terra and Aqua drifting through local time.



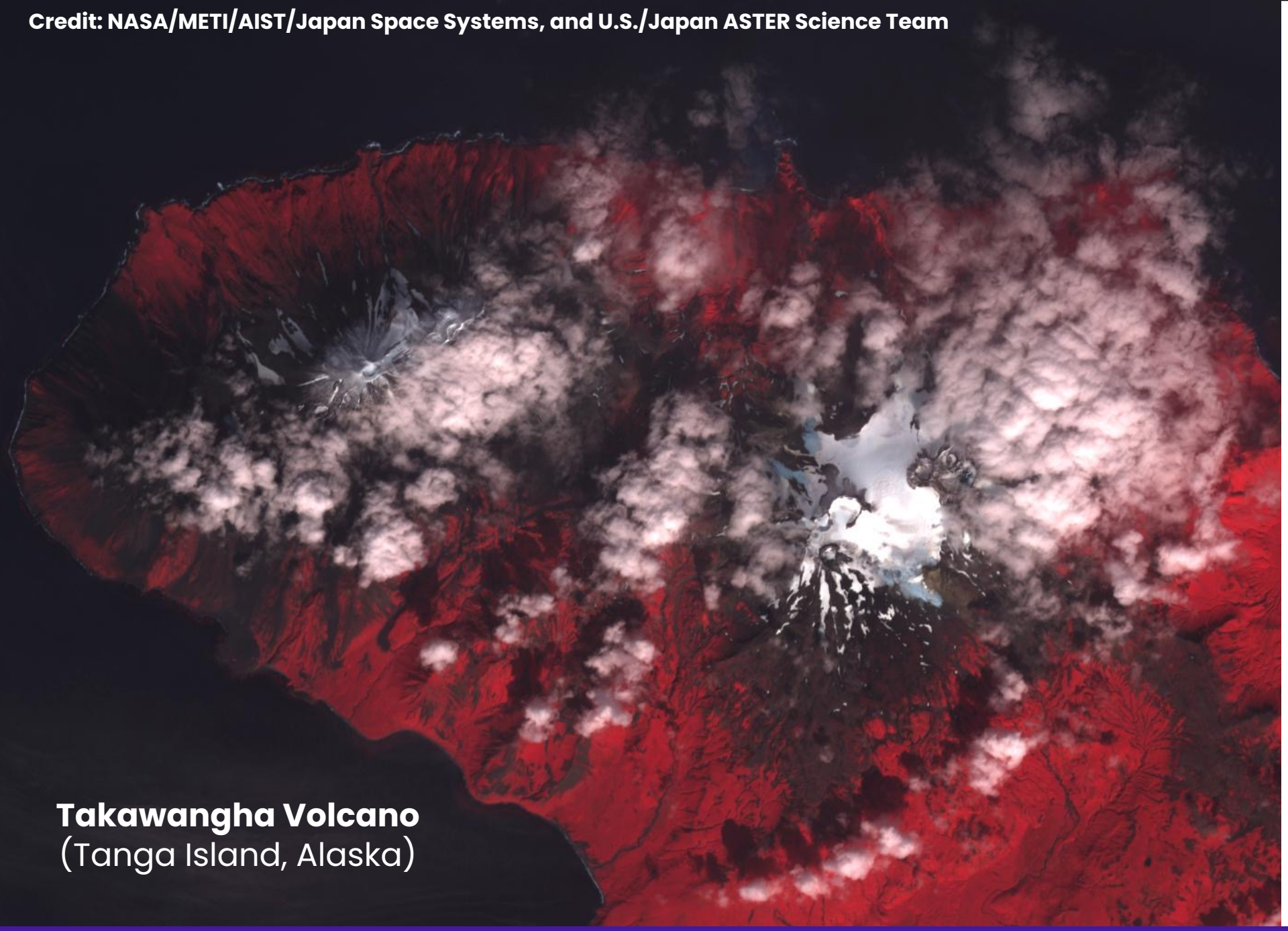
- **CERES Terra and Aqua data from drifting orbit will enable:**

(1) Test and improve scene-dependent models that describe how regional monthly SW and LW fluxes change with time throughout the day.

(2) Improve GEO imager-derived fluxes through improved narrowband-to-broadband corrections across a wide range of solar zenith angles.

(3) Targeted CERES "GEO Scan Mode" measurements over a wider range of solar zenith angles, providing a wealth of new data for improving GEO cloud property retrievals and fluxes and for studying the time variation of cloud-aerosol-radiation processes.

Credit: NASA/METI/AIST/Japan Space Systems, and U.S./Japan ASTER Science Team



Takawangha Volcano
(Tanga Island, Alaska)

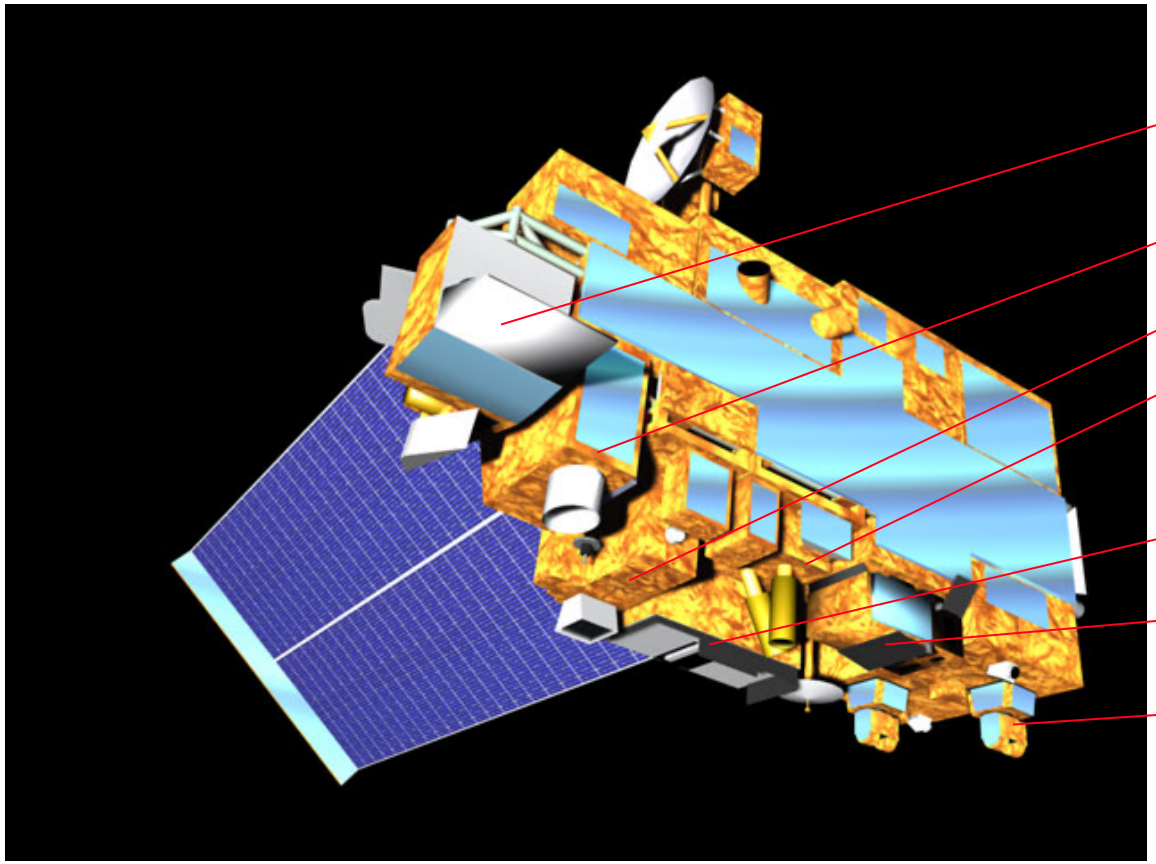
ASTER
JAPAN/USA

Michael Abrams

Terra Satellite

Terra is the flagship of NASA's ESE (Earth Science Enterprise).

ASTER is the zoom lens of Terra!

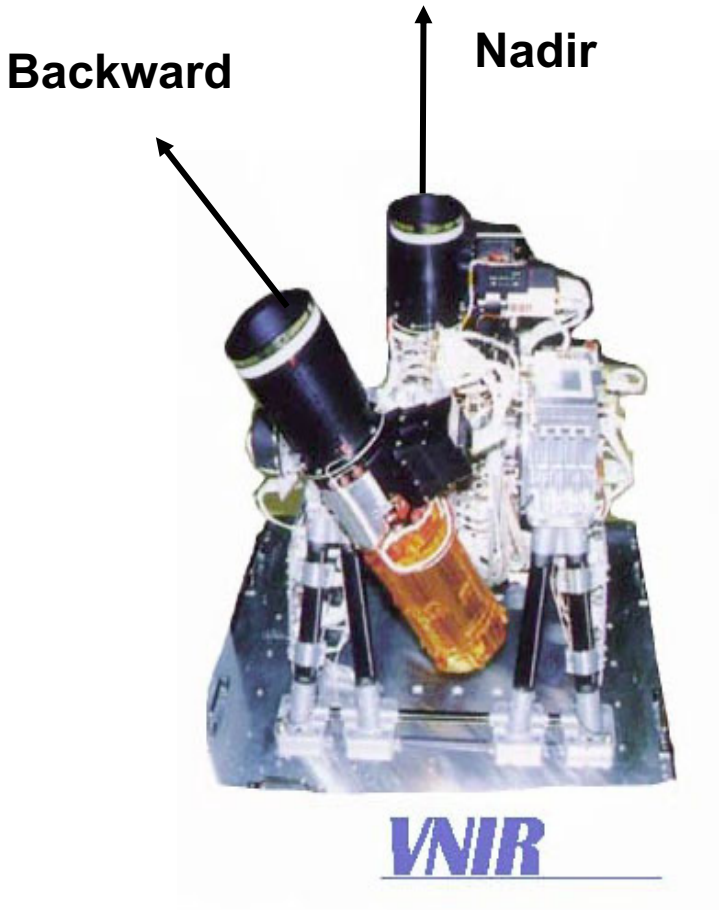


ASTER Characteristics

- **Wide Spectral Coverage**
  - 3 bands in VNIR (0.52 – 0.86 μm)
  - 6 bands in SWIR (1.6 – 2.43 μm)
  - 5 bands in TIR (8.125 – 11.65 μm)

- **High Spatial Resolution**
  - 15 m for VNIR bands
  - 30 m for SWIR bands
  - 90 m for TIR bands

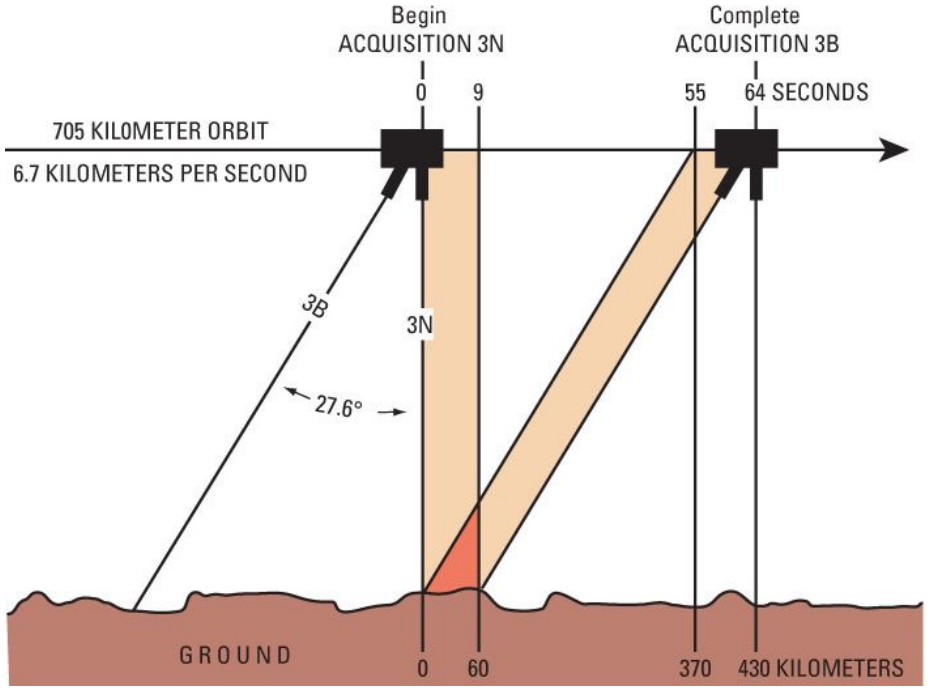
- **Along-Track Stereo Capability**
  - Base / Height 0.6
    - → Stereoscopic Interpretation
      - → Digital Elevation Model (DEM)



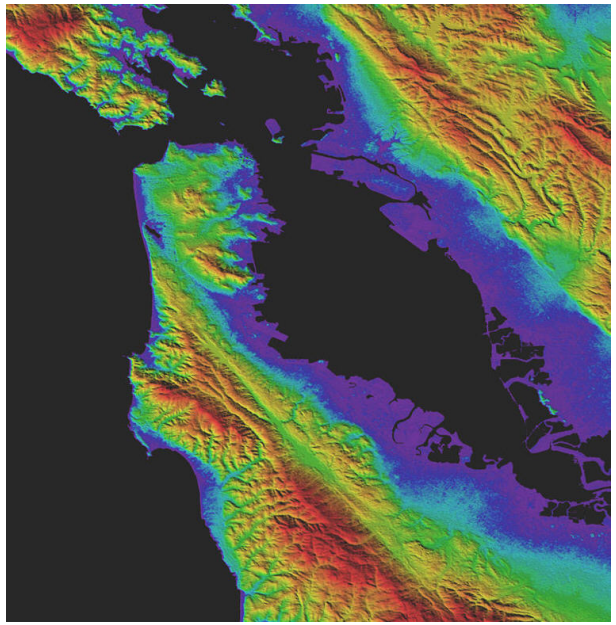
Shortname	Level	ASTER Product	Res (m)
AST_L1T	L1T	Registered Radiance at the Sensor - Precision Terrain Corrected	15, 30, 90
AST_L1BE	1B	Registered Radiance at the Sensor - Expedited	15, 30, 90
AST_L1AE	1A	Reconstructed Unprocessed Instrument Data - Expedited	15, 30, 90
AST_07	2	Surface Reflectance - VNIR & SWIR	15, 30
AST_07XT	2	Surface Reflectance - VNIR & Crosstalk Corrected SWIR	15, 30
AST_09	2	Surface Radiance - VNIR & SWIR	15, 30
AST_09XT	2	Surface Radiance - VNIR & Crosstalk Corrected SWIR	15, 30
AST_09T	2	Surface Radiance TIR	90
AST_08	2	Surface Kinetic Temperature	90
AST_05	2	Surface Emissivity	90
AST14OTH	3	Registered Radiance at the Sensor - Orthorectified	15, 30, 90
AST_L1B	1B	Registered Radiance at the Sensor	15, 30, 90
AST14DMO	3	Digital Elevation Model & Registered Radiance at the Sensor - Orthorectified	15, 30, 90
AST_L1A	1A	Reconstructed Unprocessed Instrument Data	15, 30, 90
AST14DEM	3	Digital Elevation Model	30
ASTGTM	3	ASTER Global Digital Elevation Model	30
ASTWBD	3	ASTER Waterbody Data Set	30

ASTER Data Products

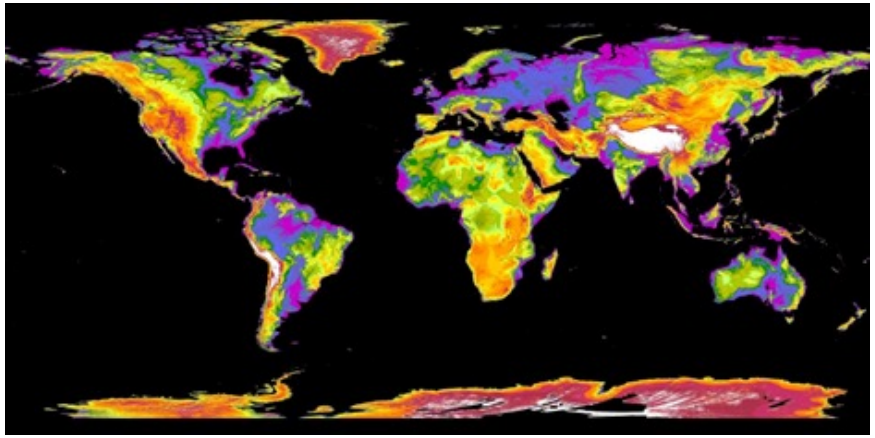
Digital Elevation Model



Stereo Acquisition Geometry



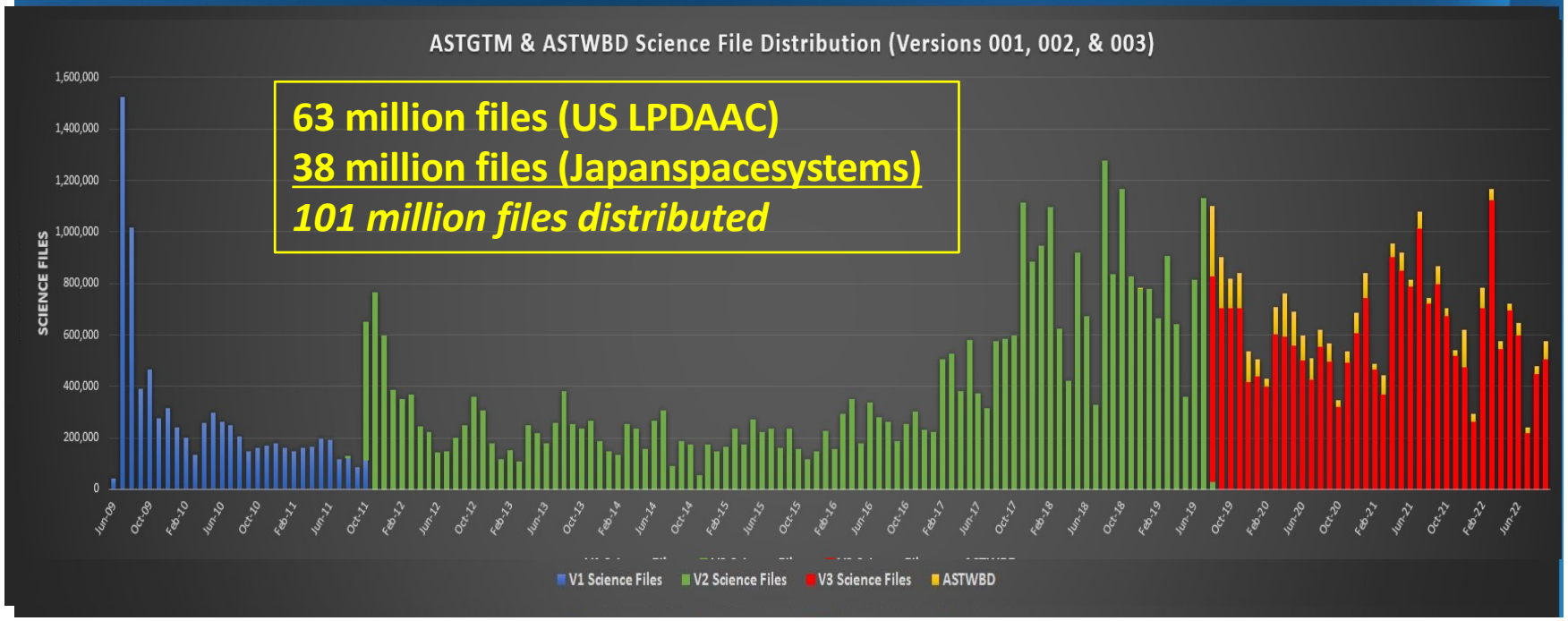
San Francisco Perspective View



GDEM and ASTWBD Distribution

V1	8.0 million files July ‘09 to Sept ‘11
V2	36.9 million files Oct ‘11 to July ‘19
V3	17.9 million files Aug ‘19 to Aug ‘22
ASTWBD	2.5 million files Aug ‘19 to Aug ‘22

Distribution History from LPDAAC



ASTER Instrument Status

- TIR & VNIR Instrument performance continues to be nominal
- SWIR Anomaly:
  - Cryo-Cooler unable to maintain detector temperature since April 2008
  - SWIR Sensor Data bands are saturated
  - SWIR powered off on September 9, 2022

ASTER TIR & VNIR are in Excellent Health
SWIR no longer provides valid science

ASTER Data in New Orbital Configurations

ASTER Data Products (1)

- L1A and L1B will have a slight change in spatial resolution (average ~1%); resolution improves in cross-track direction (closer to ground), but decreases in along-track direction (as Terra speeds up)
- The swath width becomes slightly narrower
- Since the L1T and higher-level products are resampled, the spatial resolution will remain the same; the geometric processing parameters will be maintained as before.
- The accuracy of the reference pixel during resampling will change for L1A product. There is almost no effect for higher- level products which use cubic convolution resampling.

ASTER Data Products (2)

- Scene DEMs, after orbit lowering, will have almost no change to spatial resolution of the DEM because it is created after ortho processing.

- The B/H ratio is fixed at 0.6 in the DEM. As H decreases, B also decreases, so there is no effect

Responses to RFI

Novel Fire Science

As Terra and Aqua drift, they will begin to fill longstanding gaps in moderate resolution fire detection coverage (**Figure 1**).

For Terra, the most valuable and novel data from the period of orbital drift would come from the early evening hours, as Terra slips earlier from its longstanding 10:30/22:30 crossing time to sample the decline in fire intensity over nighttime hours. The projected local time of the descending node of 21:00 by 2026 will provide novel estimates of fire location and fire radiative power (FRP) after the boundary layer has collapsed, trapping smoke near the surface and degrading air quality for communities downwind of fire events.

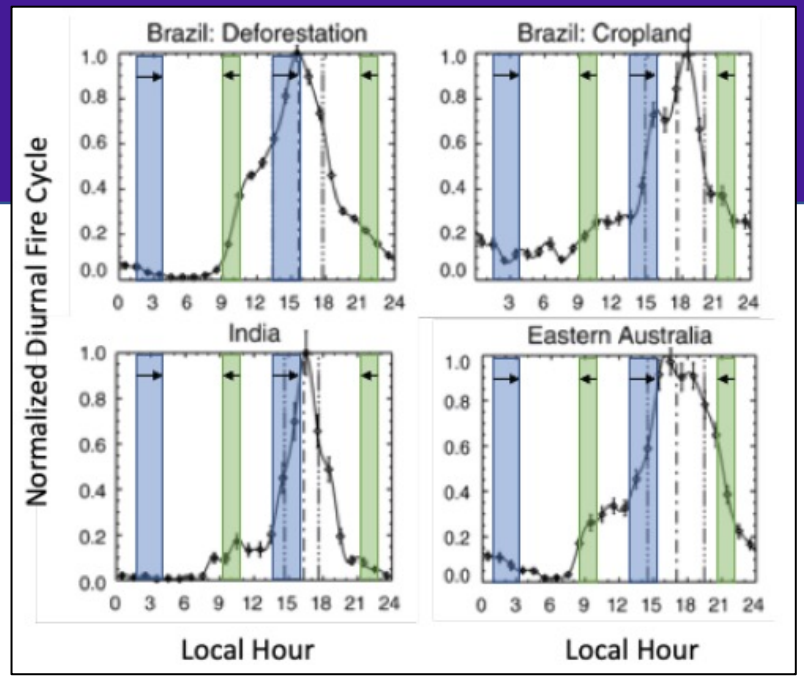


Figure 1: Fires are more common during afternoon and early evening hours that would be sampled by Terra (green) as orbital crossing times shift earlier.

Novel fire science measurements enabled by the continued operation of the Terra (and Aqua) satellites would directly contribute to the need for the development of new fire science in support of management of new extreme fires in a more flammable world. There is no cost-effective means to collect these global data in a similar time frame without the continued operation of these platforms.

Increased observations of active volcanic summits enabled by the earlier overpass times of Terra

- Because of the clouds, clear observations of an active volcanic summit occur (on average) only 45% of the time in all ASTER thermal infrared (TIR) daytime observations.
- We estimate up to nearly an order of magnitude higher increase in the number of cloud-free scenes over volcanic summit regions. This progressive improvement has already begun and will continue as earlier overpass times are realized.
- These data would improve the long-term baseline, the detection of precursory activity and eruption onset, as well as the accuracy of derived products (e.g., thermal and gas flux, digital elevation models [DEMs], etc.).

Two new studies are facilitated by Terra's earlier MLT:

(1) Earlier morning image acquisitions can have substantially fewer clouds in regions, such as the Himalayas-Karakoram. The most dynamic period for glaciers, the summer monsoon, has been missed by ASTER due to clouds. The effect of global warming is perhaps less well understood in the H-K region than anywhere else. Warming shifts snow/rain transition to higher elevations, so glacier mass balance is shifted negatively. Increased clouds and cooler summers reduce melting, leading to a positive change in mass balance. Daytime clouds have limited our seeing and understanding of what is happening.

(2) Substantially longer shadows for a given date, especially at high latitudes ice caps and ice sheets will allow us to capture fine and subtle topographic textural features. The subtle topography (missed by ICEsat-2) relates to ice flow over basal relief, wind-driven snow drifts, and glaciologically important melting and sublimation features.

ASTER Imaging of Alpine Glaciers and Polar Ice Caps and Ice Sheets for Global Cryosphere Communities

Coastal ecosystems and intertidal flats

Two new studies are facilitated by Terra's earlier MLT:

Coastal ecosystem and intertidal flats: The tidal flats' reflectance changes according to the tidal dynamics, and the 10:00-10:30am overpass time cannot capture the extreme high or low tides in certain locations. A drifting orbit when the overpass time is earlier could give several insights for bathymetry estimation or benthic mapping:

1) It will capture a different timing of the tidal dynamics, revealing a lower tide height, which would in turn reveal more of the benthic cover or bathymetry.

2) Coinciding with other satellites such as Sentinel-2 or Landsat, it will reveal the change in reflectance of the intertidal flat in that time lag, revealing the benthic cover.

Unique, Continuing Capabilities

Scene-based, high resolution Digital Elevation Models (DEMs)

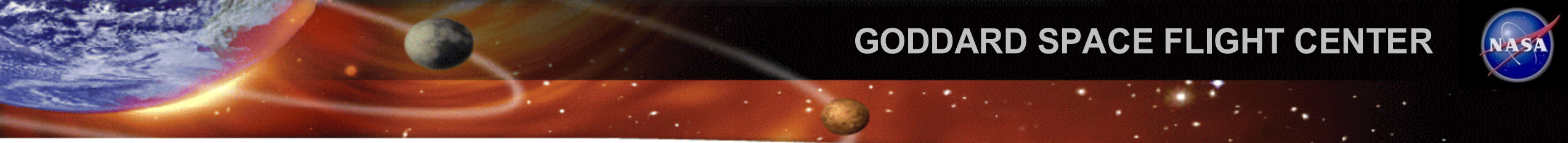
- ASTER is the only instrument providing stereo coverage (and DEMs) for EACH full mode data acquisition
- Enables change detection of topography for dynamic earth surface processes, i.e., glacier volume, lava flow volume, etc.

Multispectral thermal infrared data, global coverage, at high spatial resolution

- Complemented by ECOSTRESS on Space Station; limited to 3 bands, and mid-latitude coverage
- Next similar instrument is France-India Trishna satellite, scheduled for launch in late 2024; ASTER can provide cross-calibration to continue long-term record

Nighttime, high spatial resolution TIR data for urban heat island studies

- Acquisitions 5-10 times per month, depending on latitude



Terra's Lower Orbit Community Forum
What's next for Terra

Kurt Thome
NASA/GSFC

What's next for Terra

Terra will continue to collect valuable science data as its crossing time and orbital altitude changes

- Terra will continue to drift in crossing time with altitude slowly decaying
  - Current predictions are for Terra to reach 9:00 am crossing time in Spring 2026
  - Altitude will be 690 km in Spring 2026
- Continue data products that have made Terra data so valuable
  - Evaluate impacts from changes in equatorial crossing time
  - Determine effects from changes in nadir ground track
- Take advantage of changes in sun-sensor geometries with the current time series data sets
- Be ready for new science that will result from orbit changes
- Eventually enter Phase F and use remaining fuel to lower perigee prior to spacecraft passivation

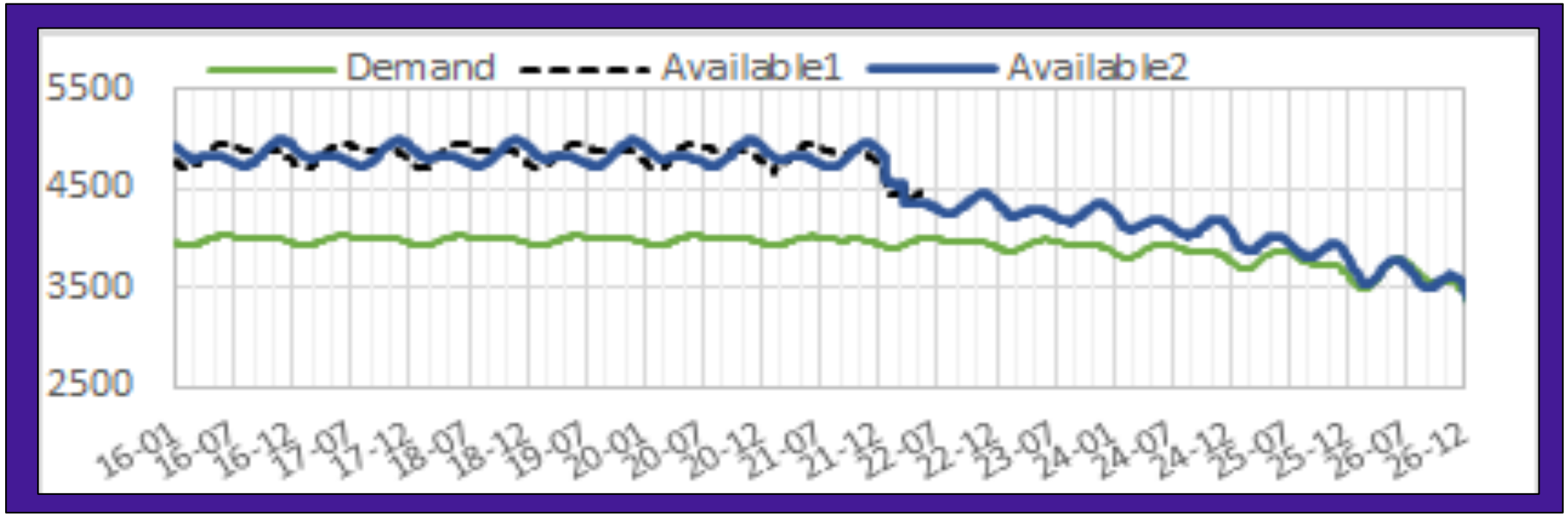
Terra is expected to be healthy - No known life-limiting hardware

- List key hardware elements and current status
- Nearly all subsystems on primary hardware
- Four non-green items:
  - ASTER SWIR is off
  - Solar array is at 88% capability
  - Batteries are at 77%
  - X-band antenna at 75%
- Solid state recorder green after 2021 reset

Subsystem	Component	Design	Current	Capability	Comments
EPS	Solar Array	24 Shunts	**21 Shunts**	**88%**	No impact to operations. Additional failures will require reducing load or EPS configuration change. Fully capable of supporting mission thru 2027 unless multiple future failures occur
	Batteries	108 Cells	107 Cells	99%	BBAT cell #50 failed on 10/15/09.
	Batteries	36 Heater Controls	28 Heater Controls	77%	BBAT heater control failed on 4 of 9 heater groups on primary, redundant, and survival. Battery cell charging/discharging and the remaining heater groups are preventing cells from freezing. PBAT heater control performance is nominal.
TCS	MOPITTCPHTS	2	2	Full	Performance is nominal
	SWIR CPHTS	2	2	Full	Performance is nominal
	TIR CPHTS	2	2	Full	Random temperature fluctuations. Performance within requirements.
SCC	SCC	2	2	Full	Performance is nominal
COMM	HGA	2	2	Full	MDA BITE failures occur 2-3/week due to SEU. Recoverable
	X-Band	2	1	75%	DAS Modulator 1 failed (50%). Solid State Power Amplifier redundancy still available (100%).
	CTIU	2	2	Full	Performance is nominal
	OMNI	2	2	Full	Performance is nominal
CDH	MO	2	2	Full	Drift rate changes have occurred since 10/3/10. Performance is within requirements.
	SFE	2	2	Full	SFE SEU occur 1-2/year. Recoverable
	SSR	59 PWA	**59 PWA**	**100%**	Successful SSR Reset on 09/22/21 recovered all 15 previously offline Printed Wire Assemblies
GNC	IRU	3	**2**	Full	Performance is nominal. IRU-B powered off. Yaw axis still redundant.
	TAM	2	2	Full	Performance is nominal
	SSST	2	2	Full	Minor loss of sensitivity in SSSTs – tracker biases updated
	CSS	2	2	Full	Performance is nominal
	ESA	2	2	Full	Performance is nominal
	FSS	1	1	Full	Performance is nominal. Not currently used
	RWA	4	4	Full	Performance is nominal. 3 for 4 redundancy
	MTR	3	3	Full	Performance is nominal
Prop	REAs	16	16	Full	Performance is nominal
Instruments	ASTER - SWIR	2	2	0%	Cooler is unable to maintain detector temperature. Science Data is unusable (Fully Saturated) and is no longer being recorded. Still collecting and monitoring Engineering data.
	ASTER - TIR	2	2	Full	Performance is nominal
	ASTER - VNIR	2	2	Full	Performance is nominal
	CERES - Aft	1	1	Full	Performance is nominal
	CERES - Fore	1	1	Full	Performance is nominal
	MISR	2	2	Full	Performance is nominal
	MODIS	2	1	50%	Power Supply #2 failed, Formatter A degraded, cross-strapped. **All Science is nominal.**
	MOPITT	2	1	50%	Displacer B and Chopper Motor failed. **Loss of redundancy only. All Science is nominal.**

Batteries and solar array

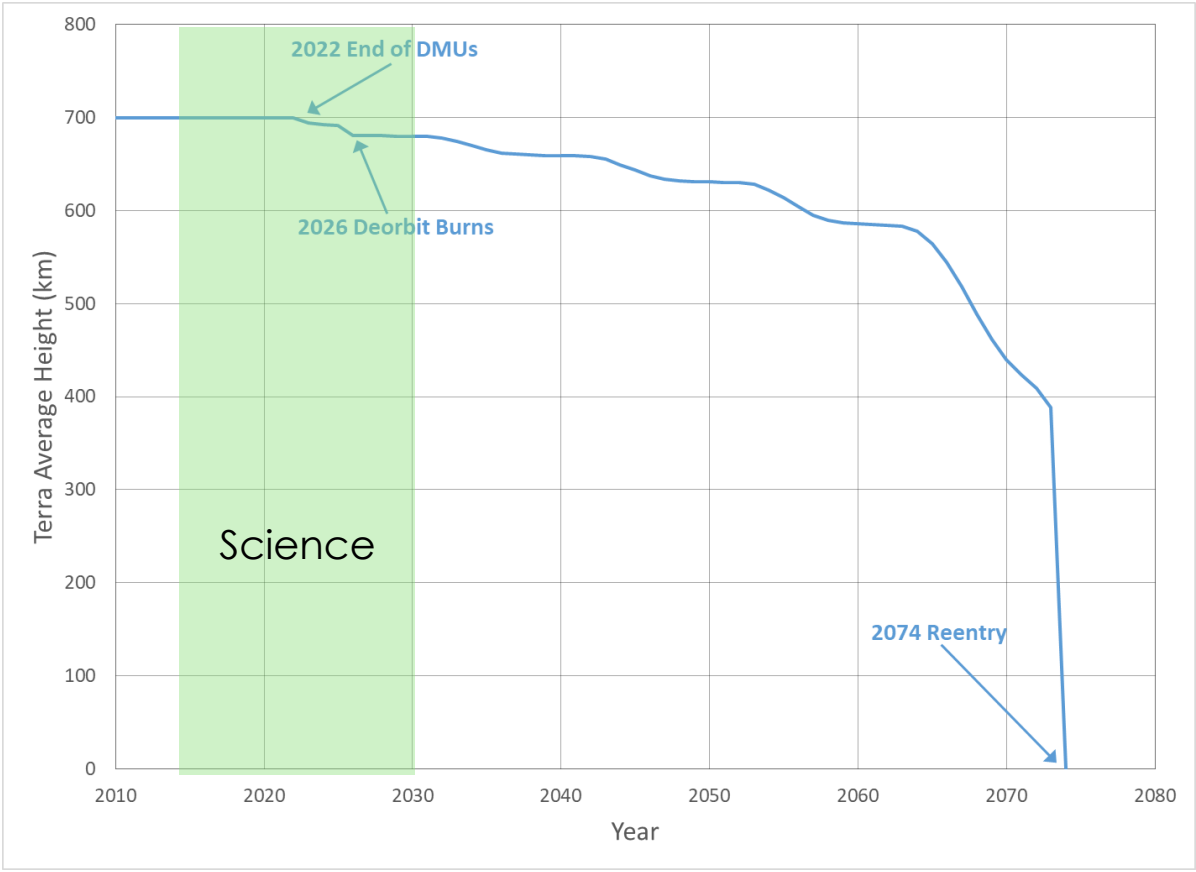
- Micrometeoroid impact early in mission affected battery operations
  - No effect on power availability
  - Operations team ensures suitable thermal conditions are maintained to improve battery lifetimes
  - 2019 study with Spacecraft Manufacturer indicated mission could continue with complete failure of one of the batteries
- Terra solar arrays have 24 shunts used to dissipate power during daytime portion of orbit
  - Three shunts have failed reducing available array power by 12.5%
  - Flight Operations Team optimized power usage leading to additional margin
  - Predictions show sufficient power available until 2026



Where will Terra be going?

Terra will eventually perform perigee lowering maneuvers as part of platform passivation

- Science acquisitions continue until perigee lowering
- All remaining fuel used to lower Terra to begin its slow re-entry to uncontrolled de-orbit
- Case shown is based on perigee lowering when Terra reaches 9 am crossing time based on the EO-1 mission decommissioning



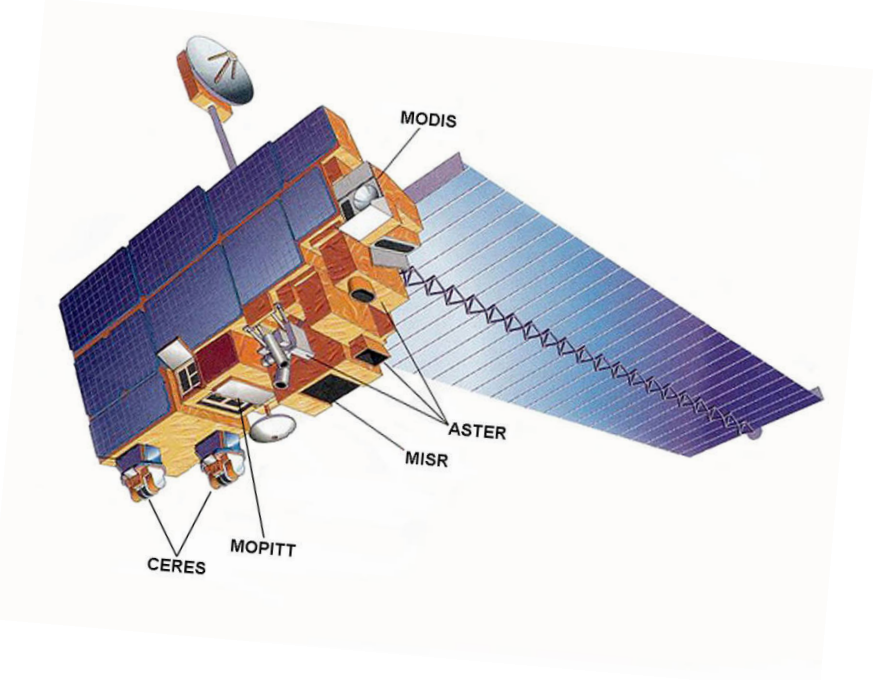
Phase F is when Terra begins this process

Phase F is the closeout phase, during which a project system is taken out of service and safely disposed

- Perform required Phase F technical activities
- Satisfy Phase F reviews' entrance/success criteria
- Dispose of the system and supporting processes
- Document lessons learned
- Baseline mission final report
- Capture lessons learned
- Ensure all data are properly identified and archived

Phase F decommissioning steps

- Notification to terminate mission sent to NASA Administrator
- Decommissioning Review held 45 days later
- Key Decision Point F review two weeks later
- Instrument passivations
- Perigee lowering maneuvers
- Platform passivation
- Passivation complete approximately 6 months after direction to terminate



Phase F data closeout

Instrument closeout is not the end of instrument team activities

- Initial 12 months of Phase F sees intense efforts to prepare data archives
  - Determine and incorporate instrument calibration updates
  - Implement product algorithm improvements
- Last 12 months consist of Implementing these updates
  - Reprocess the full data archive
  - Document algorithms,
  - Ensure safe disposition of the data and documentation
- Terra Project Science Office develops the final report
- Ensure that the user community is aware of the process

Summary

Terra science collects will continue until perigee lowering maneuvers that are part of Terra's Phase F

- Terra and all its instruments are performing well and are expected to provide high-quality data
  - No known hardware limitations
  - Platform power expected to be sufficient to at least 2026
  - Nearly all subsystems on primary hardware
- Phase F will mark the process to decommission Terra
- Data archival is a key element to the process

- Working hard towards the celebration of the 25th anniversary of Terra's First Light in February 2025

Virtual Community Forum Policies, Tips, and Best Practices

01	02	03	04
Type your questions in the Q&A box.	Keep your microphone muted & camera off until the Q&A/ discussion session starts.	Use the "raise hand" tool & don't talk over others.	Allow everyone a chance to ask questions.

Question & Answer + Discussion Session

Thank you!

From everyone working on the Terra mission, thank you for attending our virtual community forum!

If you have additional questions, please visit the Terra mission website (www.terra.nasa.gov) or email nyssa.rayne@nasa.gov.